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DATA EXCHANGE FOR INERTIAL SYSTEMS (9TH), CONFERENCE PROCEEDING--ETC(U)
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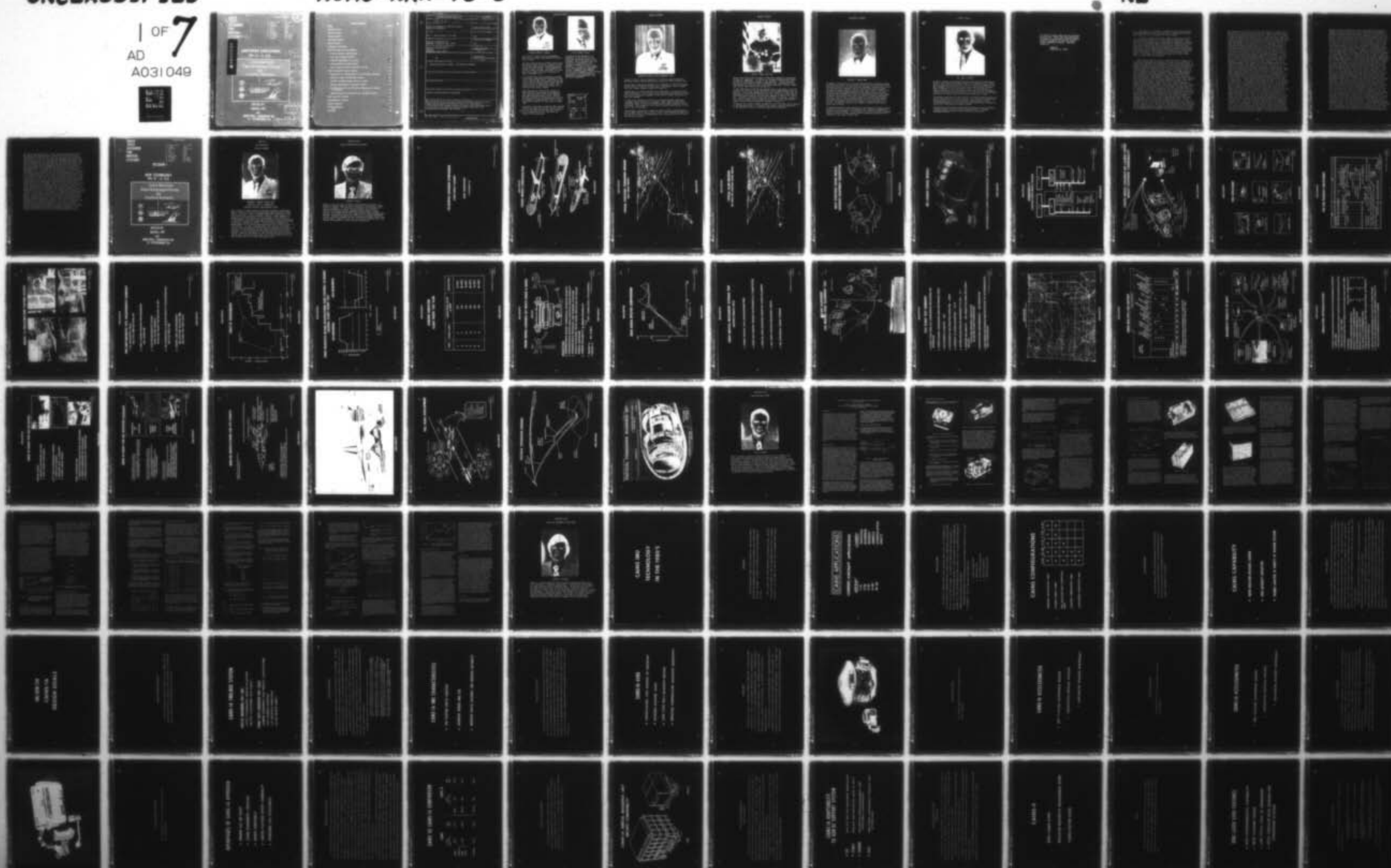

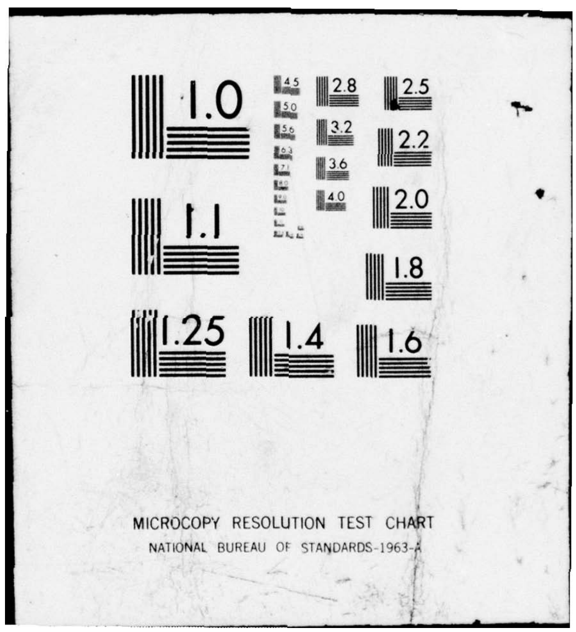

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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(6) NINTH
DATA
EXCHANGE
FOR
INERTIAL
SYSTEMS (9th)

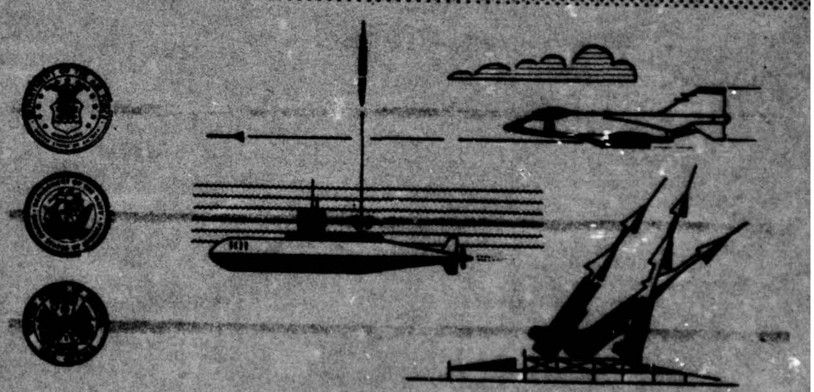
PLANNING GR

E. Bodem, Chmn
R. Creed
W. Denhard
J. Fox
J. Grillo
K. Kline
O. McClannan
R. Perdzock
W. S. Smoot
P. Zagone

CONFERENCE PROCEEDINGS,

NOV. 18 – 19 1975.

Joint Services Data Exchange Group for Inertial Systems



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Inertial Systems; Conference Proceedings

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The proceedings of the Ninth Data Exchange for Inertial Systems, hosted by MacDill AFB and Honeywell Aerospace Division, St. Petersburg, FL, 18-19 November 1975, include technical notes and texts of briefings given in the areas of New Technology, Test and Support, Life Cycle Cost, Standardization, Bearings, and Software.

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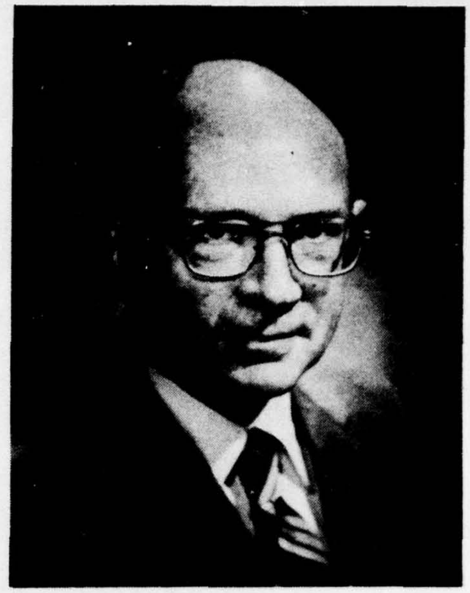
CONFERENCE HOSTS

COLONEL DANIEL O. WALSH



A. W. "BILL" KELLEY

Col Daniel O. Walsh is the Vice Commander, 56th Tactical Fighter Wing, MacDill Air Force Base, Florida.

Col Walsh entered active military service with the United States Air Force in August of 1952, having been commissioned a Second Lieutenant through the ROTC program. He attended flying school at Hondo Air Base, and Foster Air Force Base, both located in Texas; receiving his wings in December 1953.

His Southeast Asia combat experience includes a four month temporary duty assignment in 1966 flying F-100s at Ben Hoa Air Base, Vietnam and a tour with the 555th Tactical Fighter Squadron (Triple Nickel) in 1968 flying F-4Ds. He logged a total of 146 flying missions, 90 of which were over North Vietnam.

Upon completion of National War College in 1973, Col Walsh was assigned to Headquarters USAF (Pentagon) where he was Chief, Weapons and Weapons Systems Branch; Chief, Tactical Division and finally, Assistant Deputy Director of Operations for Operational Forces. He was reassigned to MacDill Air Force Base in August 1975.

Col Walsh's directions include the Distinguished Flying Cross with two oak leaf clusters, Bronze Star and Air Medal with 16 oak leaf clusters. He is a command pilot with 4100 hours jet fighter flying experience.

A graduate of the University of Minnesota, he has 25 years in the Aerospace and Defense business with Honeywell, and is presently the Vice President of Operations at the Honeywell Aerospace Division in St. Petersburg. As such, he has responsibility for engineering, production, inertial components and programs. Prior to his assignment in 197], he held the position of Vice President of Operations at the Minneapolis Aero Division of Honeywell.

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BANQUET CHAIRMAN

COLONEL WILLIAM H. BUSH, COMMANDER, AGMC

Colonel William H. Bush is Commander of Air Force Logistics Command's Aerospace Guidance and Metrology Center, Newark Air Force Station, Ohio.

Colonel Bush's previous assignment was as Commander of the 44th Strategic Missile Wing at Ellsworth Air Force Base, South Dakota, from 24 October 1973 until taking command of AGMC on 30 June 1975.

Colonel Bush is a Master Navigator with 4,400 hours of flying time and a Master Missileman. His military service spans more than 30 years in three wars and has included assignments in nine officer career fields and six major air commands.

In 1956 he was involved in the first air-dropped hydrogen bomb tests, nicknamed "Project Red Wing" at Eniwetok. While there, he published a classified report on the first airborne doppler radar navigation system, the APN-82. This system was first used on the WB-50 aircraft and is still used in the KC-135 today.

Colonel Bush's decorations include the Legion of Merit, the Meritorious Service Medal with oak leaf cluster, the Air Force Commendation Medal with two oak leaf clusters, the Presidential Unit Citation, and the Air Force Outstanding Unit Award.

JOHN W. YOUNG, CAPT USN

Captain John Young joined the Navy in 1952 after graduation from Georgia Institute of Technology. In 1962 he set the world time-to-climb records to 3000 and 25000 meter altitudes in the "Phantom." Captain Young was selected as an Astronaut by NASA in September 1962. He served as pilot with command pilot Gus Grissom on the first manned Gemini flight in March 1965 and was later backup pilot on Gemini 6.

In July 1966 Captain Young was the command pilot on the Gemini 10 mission. Following this mission, he was assigned as backup command module pilot for Apollo 7. He was then command module pilot for Apollo 10 in May 1969, the comprehensive lunar-orbital qualification test of the Apollo lunar module. His fourth space flight was as Spacecraft Commander of Apollo 16 in April 1972. Captain Young spent 71 hours and 14 minutes on the moon, logging 20 hours and 15 minutes in extra-vehicular activities. After that mission, Captain Young was backup Spacecraft Commander for Apollo 17.

In January 1973, he was assigned responsibility for the Space Shuttle Branch of the Astronaut Office. In January 1975, Captain Young was named Chief of the Astronaut Office for the Flight Operations Directorate.

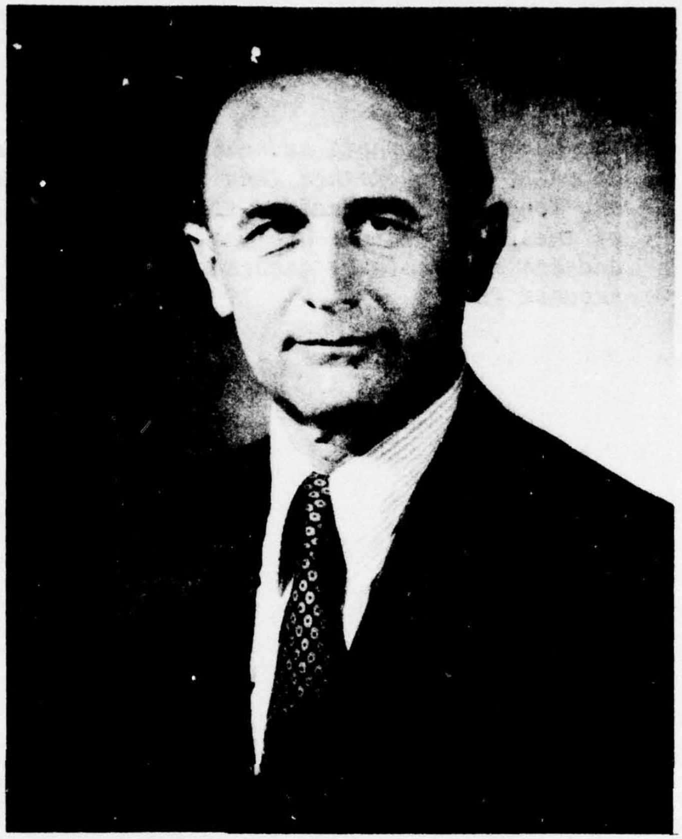
CONFERENCE CHAIRMAN

MR EARL T. BODEM, AGMC

Mr Bodem is the Director of Plans and Programs Office, Aerospace Guidance and Metrology Center. He has served over 30 years with the US Air Force. During this period he has held staff and management level positions at the Air Force Logistics Command in Dayton, the Air Force Systems Command, Aeronautical Systems Division and at Hickam Field, Hawaii. While at the Air Force Logistics Command Headquarters Mr Bodem conceived the idea, developed and implemented the initial planning which led to establishment of the Air Force single point repair of inertial systems at the Newark facility. Over the past 17 years Mr Bodem has received three Superior Performance Awards, two Outstanding Awards as well as the Meritorious Civilian Service Medal which is the highest civilian award for Civil Service. Mr Bodem has prepared and released a number of publications within the Air Force.

Mr Bodem obtained his formal education at the University of Dayton and the University of Michigan and has graduated from a number of Department of Defense training programs. He originated the Joint Services Data Exchange Group for Inertial Systems and has served as permanent Secretary since inception of the group in March 1969.

KEYNOTE SPEAKER



DR JOHN J. MARTIN

Dr John J. Martin was appointed Principal Deputy Assistant Secretary of the Air Force (Research and Development) on 29 September 1974. During WW II he served as a Naval Officer - while in service he studied at the Naval Academy, Harvard and MIT, later he received his MSME from Notre Dame in 1950 and his PhD from Purdue in 1951. He has worked as a research engineer for North American Aviation and later for the Bendix Aviation Corp where he progressed from Sr Engineer to Chief of Engineering Research at the Bendix Advanced Development Laboratory in 1959.

He has been associated with the Institute for Defense Analysis and on the staff of the President's Science Advisor. More recently, Dr Martin was Associate Deputy to the Director of Central Intelligence for the intelligence community and in 1974 he was appointed special assistant to the DCI for intelligence information systems.

Dr Martin has written several monographs and papers and has disclosed a classified patent "Ballistic Missile Defense System." His book, Atmospheric Reentry (1966) has been translated into Russian.

Dr. Martin's keynote address was not available at press time. Rather than delay publication any longer it was decided to print the balance of these proceedings and make the keynote address available by request. Send your request to:

AGMC/XRX
Newark AFS OH : 43055

". . . The purpose of a keynote is generally to give some direction - some ideas about how things are seen from a different point of view with respect to the work a group like this is doing.

We are in a time of flux with respect to the field of technology that INS is imbedded in. I don't mean to restrict the text just to the technologies and the circumstances surrounding it dealing with INS, but to restate that we really are in a state of flux these days - to the degree that those of you who are interested in the technology - those of you who are interested in systems applications - those of you who are businessmen and those of you who are researchers - to the degree you are able to perceive and respond to that flux will determine progress. I am confident we will come through in good shape. It is a time to be fast on your feet and to keep in touch - that, in a few words, is my keynote . . . "

I came here to talk to you for a little while and I suspect that at least to some degree you came here to listen to me for a little while, and I'm going to try to make sure I get finished before you get finished and keep an eye on the door. The purpose of this meeting, of course, is inertial navigation systems and I've already said that at lease for these first few words that I'm going to convey to you I'm really talking in a somewhat larger context. That larger context is the whole field I would say of command, control and communications and I think that the technologies that you apply borrow from that field and feed into that field and so that the things I am going to say in this wider C cubed context, I hope you will apply those interests which you have and if they are wider than mine is, then I would apply them a little bit wider. Earlier this year, in Spring in fact, Secretary McLucas asked a number of us, Jack O'Neill, General Jack O'Neill who is now retired and I, and in fact one of your what I understand is called the guidance mafia , John Hepfer, and some others to get together to see what the prospects were for the Air Force in the C-3 area and we studied this matter for two or three months, and we put out a report about one-half inch thick which essentially gave what our perceptions were. I kinda scooped them a few minutes ago when I said that it is a time of flux; it really is that; there are wonderful opportunities. We are in a kind of technological change that keeps bounding ahead and we do not have to keep up with that. I would recommend to you if you have the opportunity that you try to read that report. You can't do it justice in a few words and I'm not trying to do that here now, but it really gives some impression of what we foresee for the coming 10 years. In fact, I would give credit to Jack O'Neill for perceiving that perhaps between 1955 and 1965 we were in a decade that was dedicated to the missile, particularly the ballistic missile,

and probably about 1965 we came out of that woods, so to speak, and in fact the work of this group, or at least its members, undoubtedly contributed to our getting a lead in that area. From '65 to '75 I believe we have been back in the aircraft area. The Air Force has brought out a number of wonderful new aircraft, some of them are already operational, others have gone through the prototype and will soon be going into full scale development. The F-16 is what I have in mind in particular. I think that decade of the airplane while it is continuing, and we will have those wonderful aircraft with us for some time, essentially is completed and I really believe and this I'm saying out of tribute to Jack O'Neill that we are really entering the C cubed decade and I think that if we can think of it in that kind of a context, that is to say, one in which there is some thrust for the next few years and we should try to maximize its effect in our defense interests. I think that 10 years from now when someone stands in a place like this, he will be able to say that we have succeeded in the C cubed decade just the way we did in the aircraft decade and in the ballistic missile decade and I would exhort you to go to those lengths. This talk I said some moments ago was going to be about standardization and its benefits and costs. The benefits are I think pretty obvious, at least as we try to think about them in the Air Force, We want to have cheaper acquisition costs, cheaper maintenance, interoperability and those are all the good things that we would like to get through. There ought to be some benefits for those of you who are the providers of those systems and I think if we can get to the circumstances that we are working toward (I'll talk about those in a few minutes) it will offer benefits to you in the way of having easier ways, lower thresho lds to cross in introducing technological breakthroughs that you are developing. I think there will be some costs and I'm not talking in dollar costs, I am talking in other kinds of costs. It is certainly going to be a more challenging time for those of us in the government who are trying to manage with the flexibility that will permit this kind of benefit to be realized in that we will have to be more open minded; we will have to be willing to be subject to change all the time. On the other hand, those that provide systems will not likely be in the position where they can say, well, I've got this system and I'm going to produce it for X years, I'll just keep stamping them out. There will always be that cost to be paid which deals with an implicit threat that with the kind of standardization-interoperability it will be easier to make changes and one will need to keep that competitive edge all along. Now, there is another cost and that is outside the context of U.S. interests, and that is the desire to have standardization with our NATO allies. The President has spoken on the subject. It is a DOD policy that we will move in that direction and what that will mean is that the industrial concerns in Europe and perhaps elsewhere will want to share in the production that goes into the machines like the F-16 that we procure in common. I visited some of the NATO

nations a couple of months ago just on the subject of interchange of information and what that might lead to, and I think that they are learning a lesson from the concessions, if that's what they are, that we made in the case of the F-16 to the consortium, that is to say, the flexibility with which we are willing to do business with our NATO allies. I think that another one of the costs that will be paid is that there will be competition from quarters though we have not seen it before and I think that will be a cost that some of you will feel and some of us will look upon it as a policy direction that we need to implement because we just can't keep sending our hardware to our NATO allies and taking their money in return. I think that is going to have to be a two-way street. The sooner that we all understand that, the better off we will be. I said that it's the policy of the executive department of government that we will move in that direction. In the Congress, itself, some folks are in favor of some of that work in common, others are not. I think that we will have to continue the educational process that will cause there to be a general understanding and a common understanding of what our vest interests are and that we move in that direction. As for our NATO allies, those that I talked to were quite pleased with the notion that we were moving in that direction, that it was an approach that we were trying to take, and their main response was how do we do this and I think that we will have to be helping them in that respect in the months ahead. I said that we are in a time flux. What we are really trying to do these days is to break some new ground in our efforts to reduce costs. We have a list of abbreviations associated with concepts that we apply. We design to cost, we consider the life cycle costs, we talk about reliability improvement warranties, fault-free warranties, value engineering changes, etc. We even talk about our return on investment and nobody really has been clever enough to figure out exactly what that means. Now there are some cases in which one can talk about return on investment, but we have introduced these several concepts that cover various aspects of problems that we have seen, and we are going to have to have a better understanding of that. But in any case, we have begun to develop an arsenal of ideas that will permit us to respond to the costs that we see which continue to rise. We will try, by the procedures that we use in contracting and procurement, to bring incentives that are worthwhile incentives, on costs and schedule and performance, Giving to those who are making the INS what they need in the way of some return on the investment that they make, on the other hand, gives us what we need in the Air Force for the utilization of our missiles and aircraft. We have invented recently something called a Life Cycle Cost Council, John Toomey and Dewey Logan, probably as most of you know are the co-chairmen of that, and there are a few other people in the Secretariat who are members of that council. It's a recognition that we need to gather together ideas which are appropriate to this subject and to try to give them some common focus

and to put them into action. In fact, what we are trying to do is be careful that quoting Lincoln I gues it was, that we avoid the circumstances in which we say, "don't get it right, get it written," which is to say, "the hell with what the structure of the facts are, let's get on with it." We are trying to understand what we are doing at the same time that we are required to be taking some action. The Chief of Staff of the Air Force has come forward with an idea which has been captured in the nickname PRAM which I'm sure you've read about which stands for productibility, reliability, availability, and maintainability. I think this is another aspect of the notion of designing to cost, RIW, FFWs, etc, but there are just a lot of strings all leading to the concepts of how do we get standardization, how do we get interoperability. One of the first things that the Life Cycle Cost Council is going to do is to try to pool these ideas that I named to you, ETC, LCC, RIW, FFW. In fact, we talk in that jargon so much, I intentionally did that to try to make the point that we almost sometimes forget about the meaning of the words and let them take on a meaning that suits the occasion. One of the first things we are going to do in this council is understand what the process is into which these concepts fit so that we know when we want to apply them, to what degree and that we don't overcorrect or put needless loads on the people who are trying to respond to the meaning in the product divisions of the Air Force, in our laboratories, in laboratories elsewhere and in industry. We are making that effort and we need your help in that effort. What we want to get out of this work in the Life Cycle Cost Council and PRAM is some idea of how to evolve the concept of these ideas as separate ideas into a theory (I don't want to sound too analytical or too removed from reality) but to try to understand what the structure is into which they fit, try to evolve that into a practice, and then after awhile try to establish a policy which can be well enough known that, knowing the rules of the game, we will all know how to respond to them and work together harmoniously. Our motivation in the Air Force is to get the performance we require.

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

PLANNING GROUP

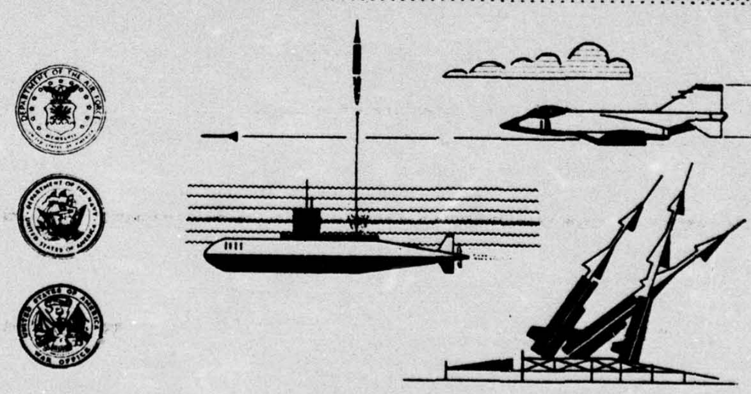
E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

SESSION I

NEW TECHNOLOGY

NOV. 18 – 19 1975

Joint Services Data Exchange Group for Inertial Systems



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SESSION I

NEW TECHNOLOGY

SESSION CHAIRMAN

RICHARD T. GODDARD, MAJOR, USAF

DIRECTOR, INERTIAL ENGINEERING

AEROSPACE GUIDANCE AND METROLOGY CENTER

Major Richard T. Goddard became the Aerospace Guidance and Metrology Center's Director of Inertial Engineering at Newark Air Force Station, Ohio on 1 May 1974. He was assigned to AGMC after completion of the Armed Forces Staff College in Norfolk, Virginia. Major Goddard is a graduate of the United States Air Force Academy, with a Bachelor of Science Degree in Engineering and the aeronautical rating of a Navigator. He received his Master of Science Degree in Aerospace Engineering at the University of Southern California. In 1965 he was assigned to the Undergraduate Pilot Training Program and later was an instructor pilot in T-37 aircraft. He later completed combat crew training in the RF4C aircraft and was assigned to the 14th Tactical Reconnaissance Squadron in Thailand. In 1972 he became the Wing Chief, Reconnaissance Tactics, involved in flying and planning of reconnaissance missions over North Vietnam. Among his decorations are the distinguished flying cross with one oak leaf cluster, the bronze star, the Air Force medal with 15 oak leaf clusters and the Air Force commendation medal.

GEORGE E. SCISM

George E. Scism has been in Avionics and Guidance for 18 years. He started at Douglas Space and Missile Division at Santa Monica, headed Skybolt at Douglas. Mr Scism came to McDonnell in 1959 worked on Advance Programming for years, including global range missiles, anti-missile programs, headed rendezvous guidance early in Gemini Program. Also headed G&C on Boost Glide Re-Entry Vehicle Program which McDonnell developed and tested for SAMSO as part of ABRES development program. Program management terminal guidance environment effects also part of ABRES. Head of avionics for cruise missile program and is now engineering management on cruise missile guidance set.

TRI-SERVICE GUIDANCE SYMPOSIUM

CRUISE MISSILE GUIDANCE

MDAC PRESENTATION

18 NOVEMBER 1975

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CRUISE MISSILE CONFIGURATION

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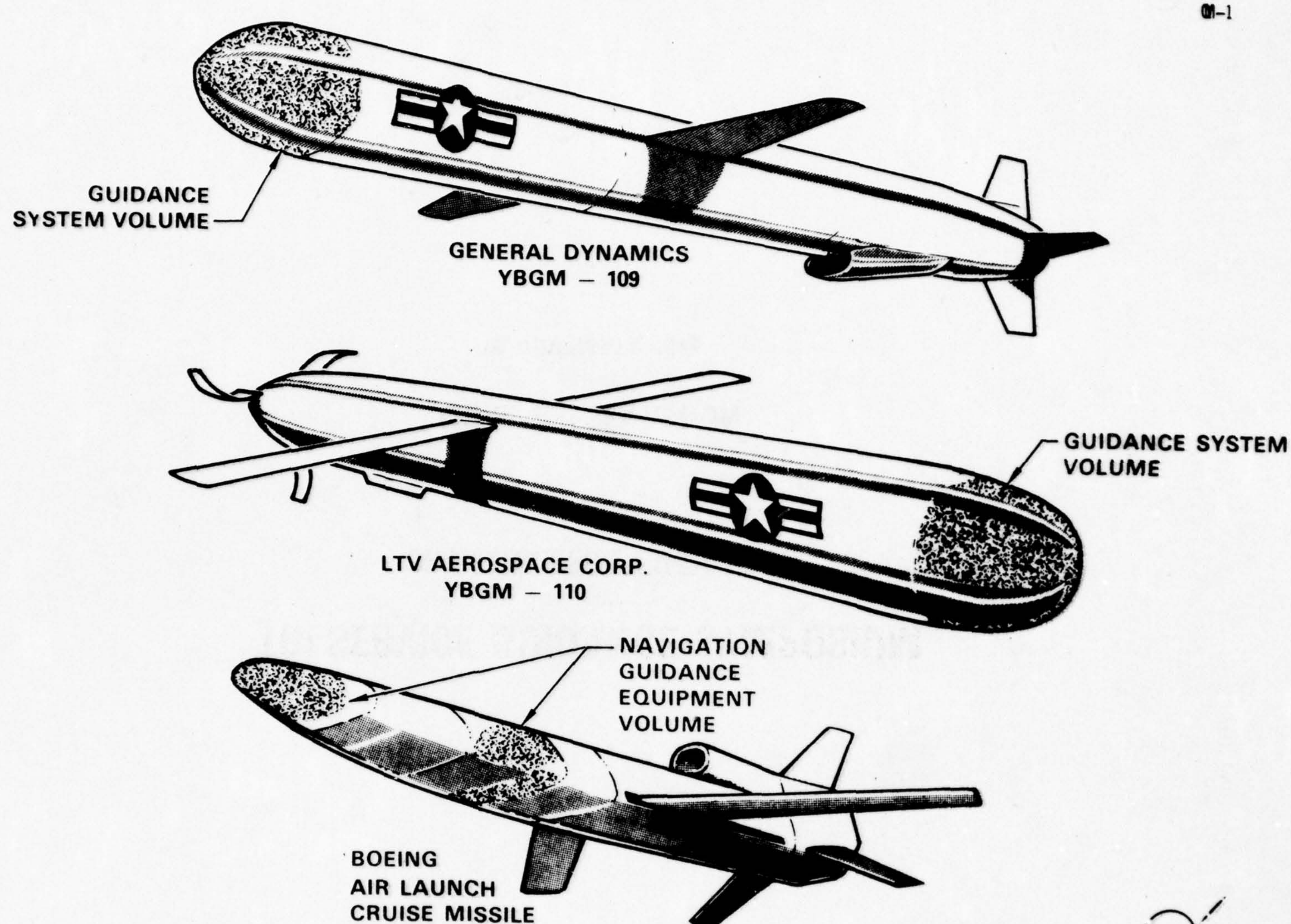

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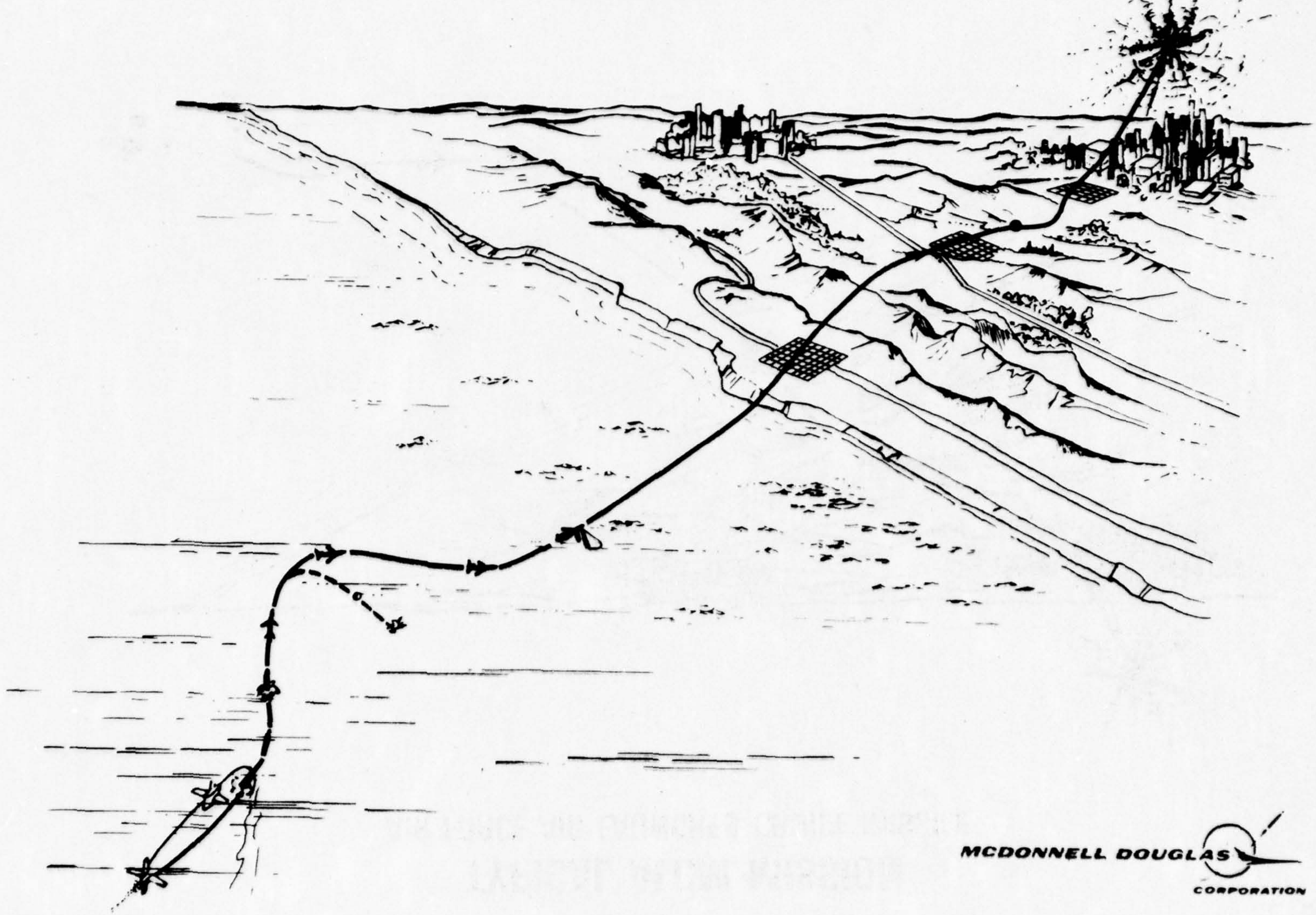
TYPICAL STRATEGIC TOMAHAWK MISSION
NAVY CRUISE MISSILE



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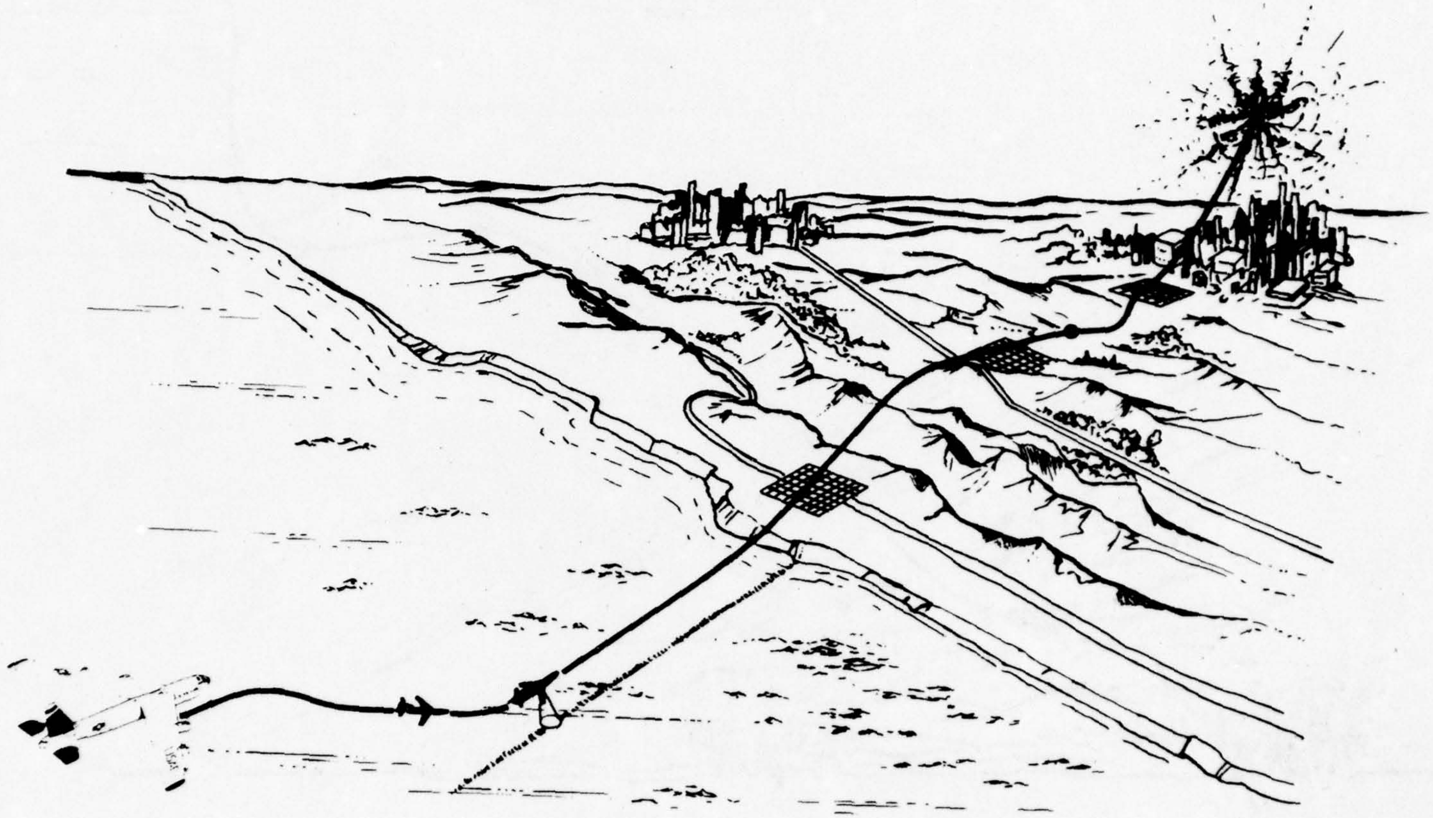
TYPICAL ALCM MISSION
AIR FORCE AIR LAUNCHED CRUISE MISSILE



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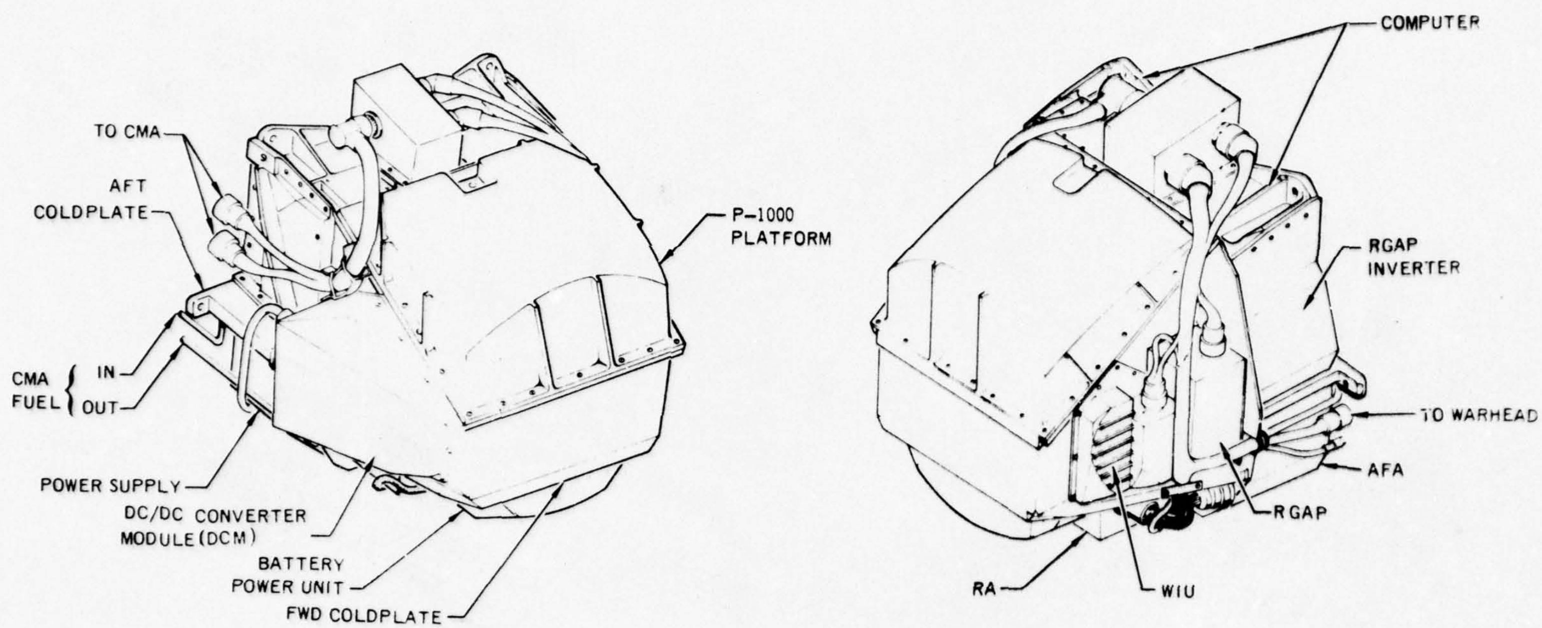
NAVY STRATEGIC CRUISE MISSILE GUIDANCE EQUIPMENT DESCRIPTION



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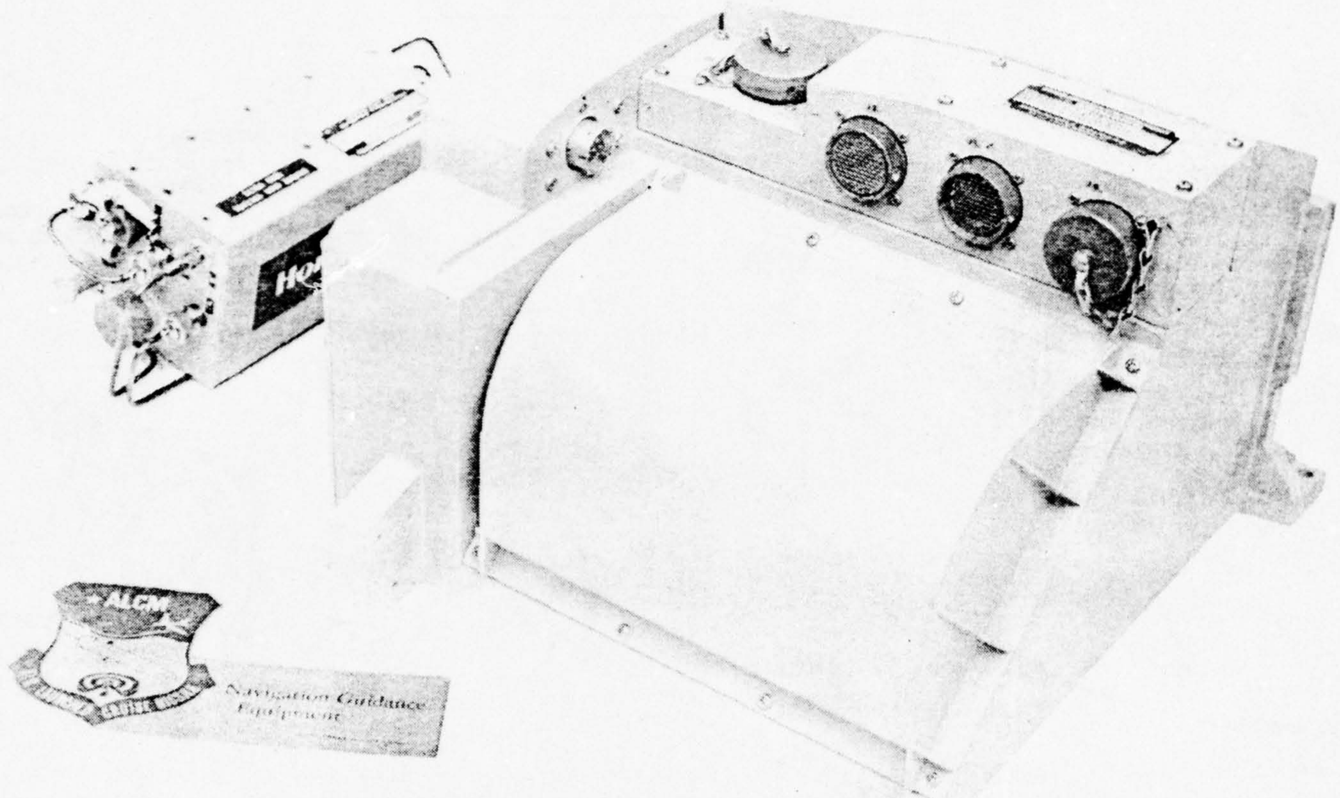
AIR LAUNCH CRUISE MISSILE



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STRATEGIC CRUISE MISSILE GUIDANCE

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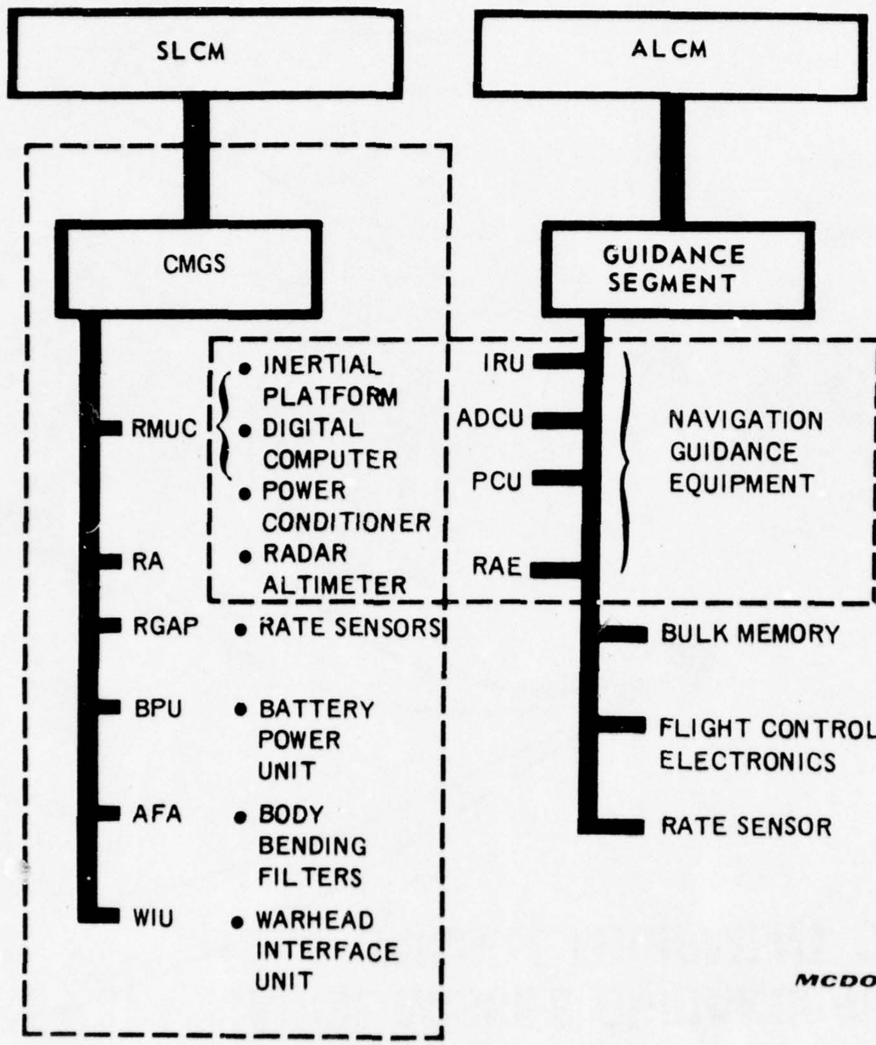

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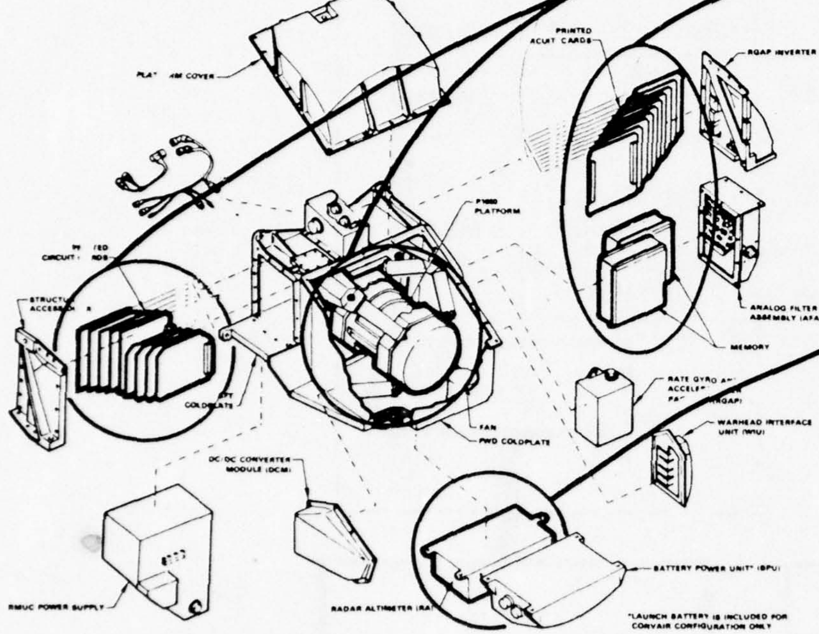
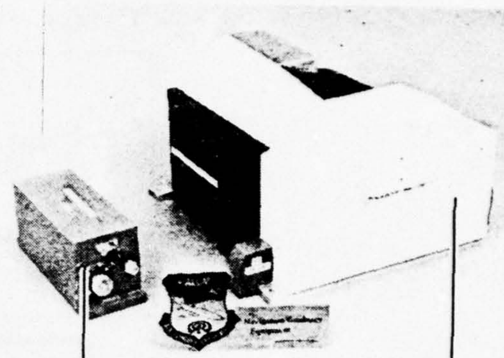
CRUISE MISSILE GUIDANCE/AIR LAUNCH CRUISE MISSILE EQUIPMENT COMMONALITY

PRIOR
AGM–86A
HARDWARE

- P–1000 PLATFORM
- LC–4516 COMPUTER
- AN/APN–194 RAE



Strategic Cruise Missile Guidance
Set Subassemblies



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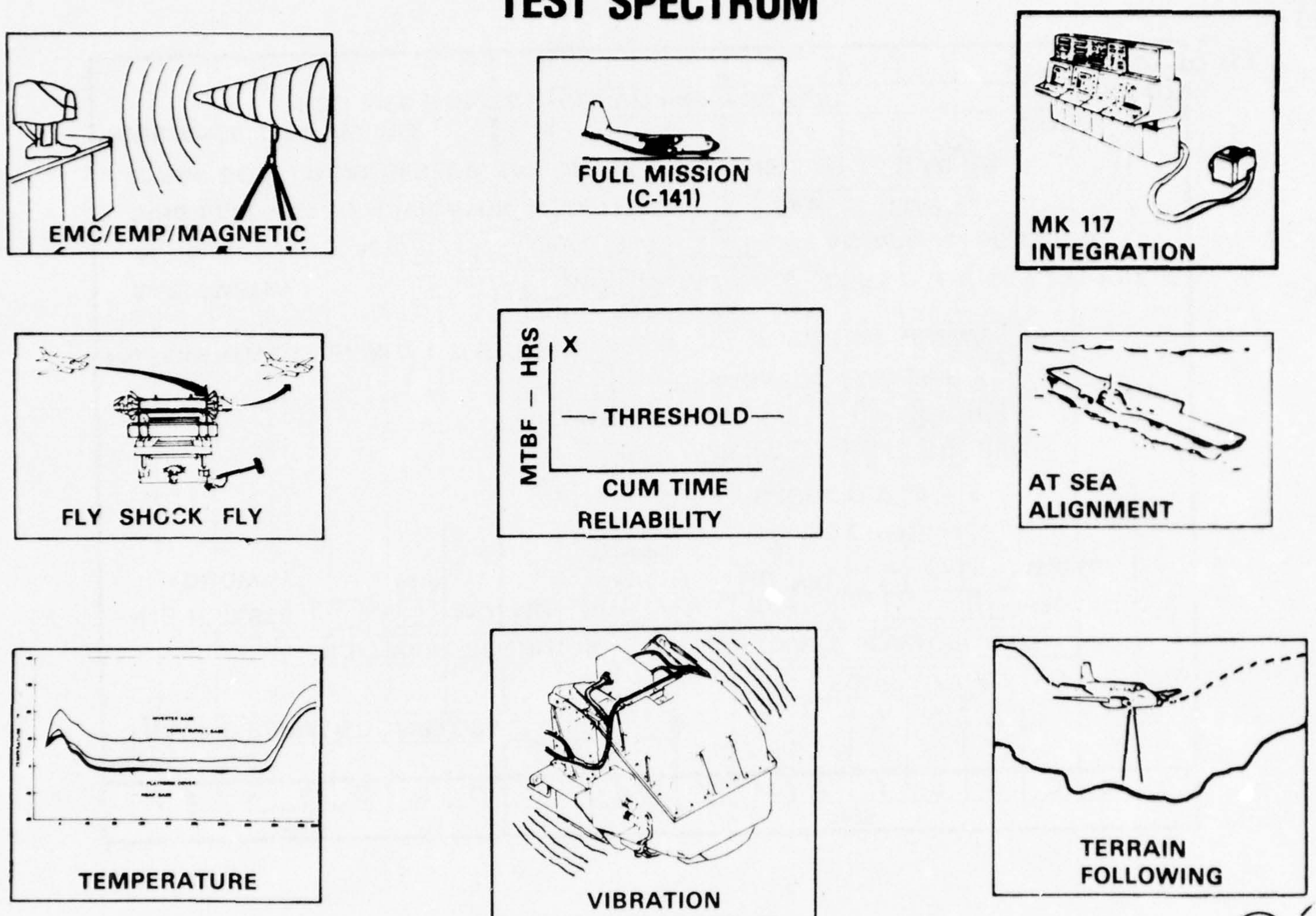
TEST SPECTRUM



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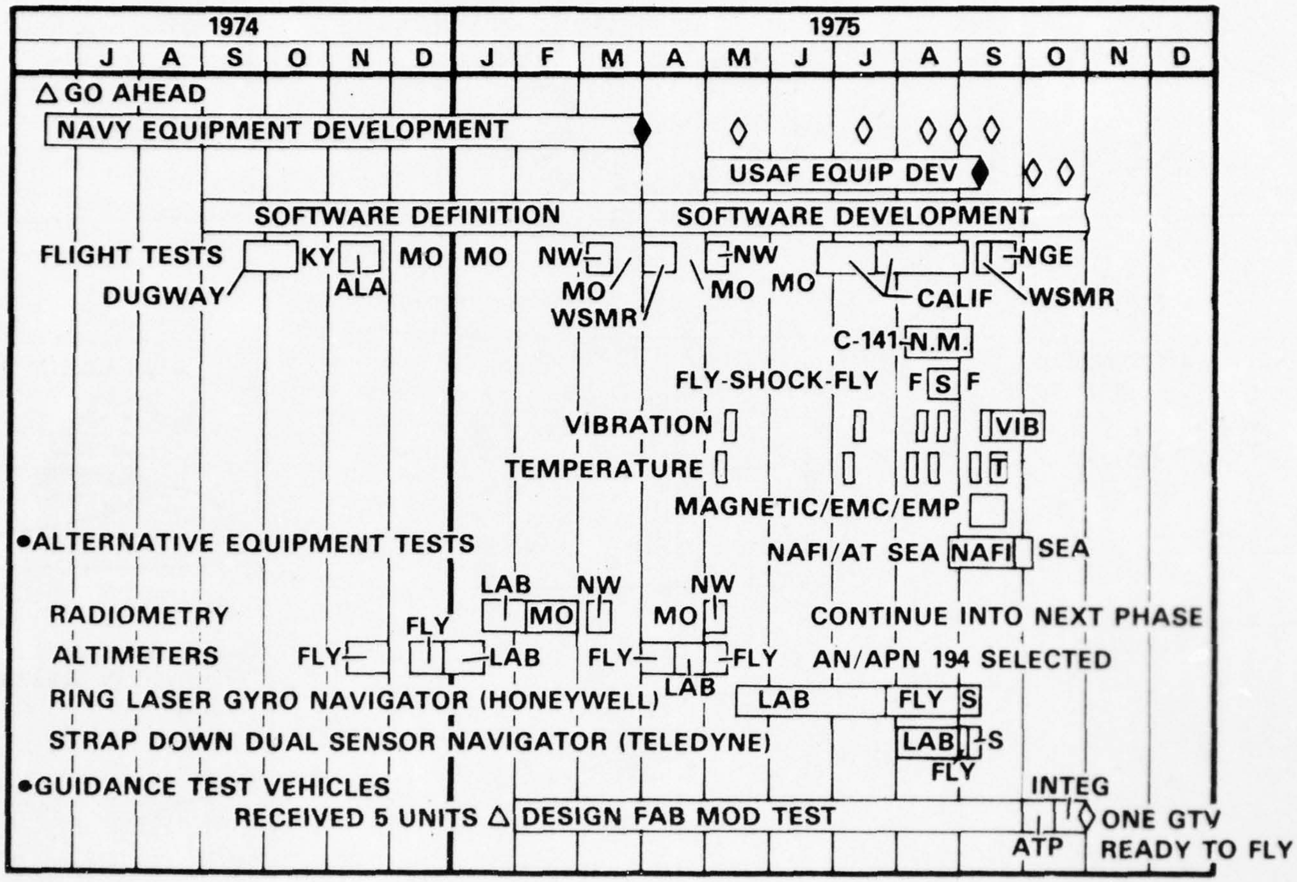
THE CDS SCHEDULE MILESTONES



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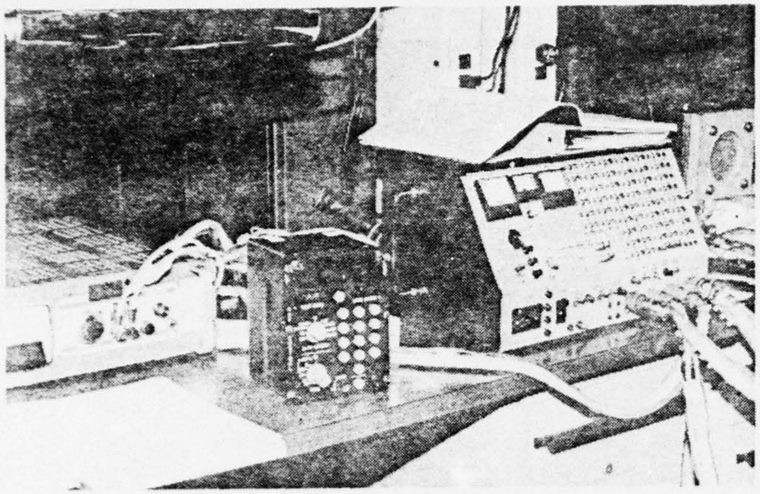
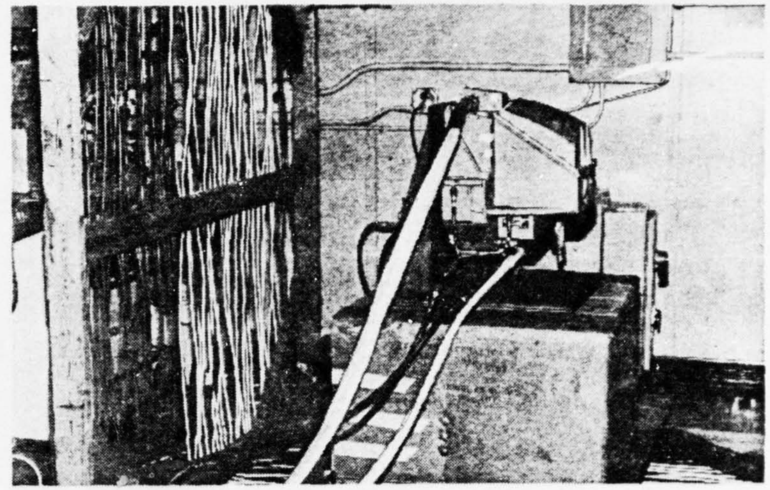
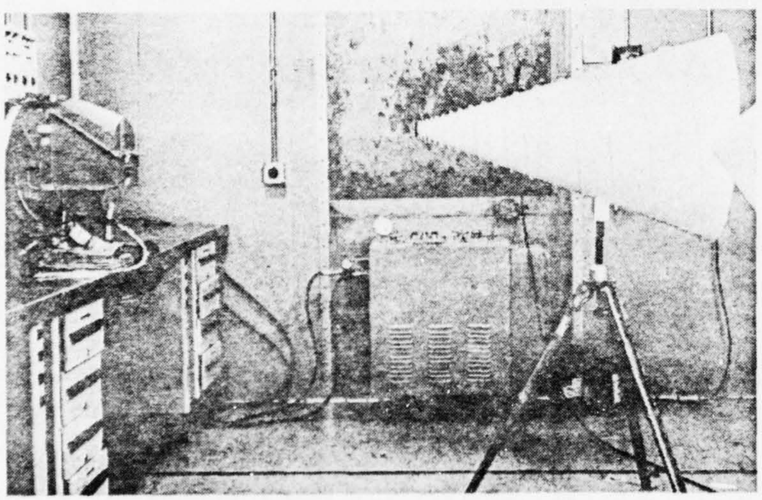
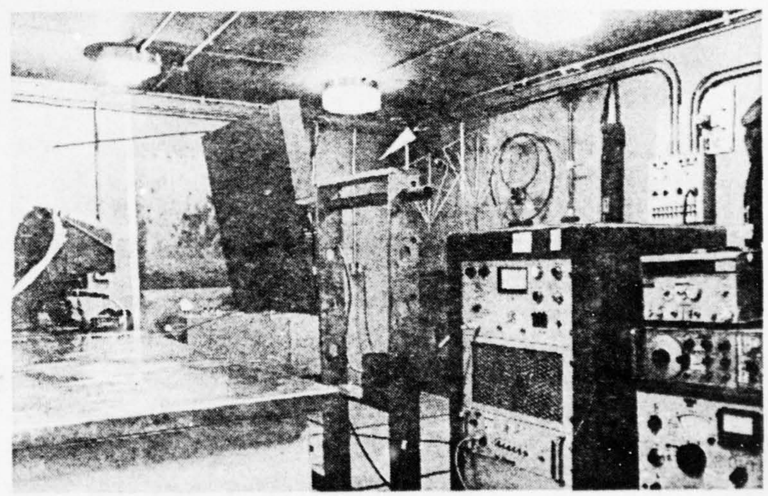
MAGNETIC FIELD/EMC/EMP TESTING SETUPS









MCDONNELL DOUGLAS CORPORATION

3-1306A

EMC/EMP/MAGNETIC TEST REQUIREMENTS SUMMARY

1. DC MAGNETIC FIELD
   MIL-STD-1399 SECTION 401

2. HIGH POWER RADAR ENVIRONMENT
   MIL-HDBK-235

3. ELECTROMAGNETIC PULSE
   FREE FLYING MISSILE —
   NUCLEAR BLAST DEFINITION IN RFP

4. EM EMISSIONS & SUSCEPTIBILITY REQUIREMENTS
   MIL-STD-461A/462

5. POWER LINE ENVIRONMENT
   MIL-STD-704; MIL-STD-1399,
   SECTION 103, CMA ICD'S

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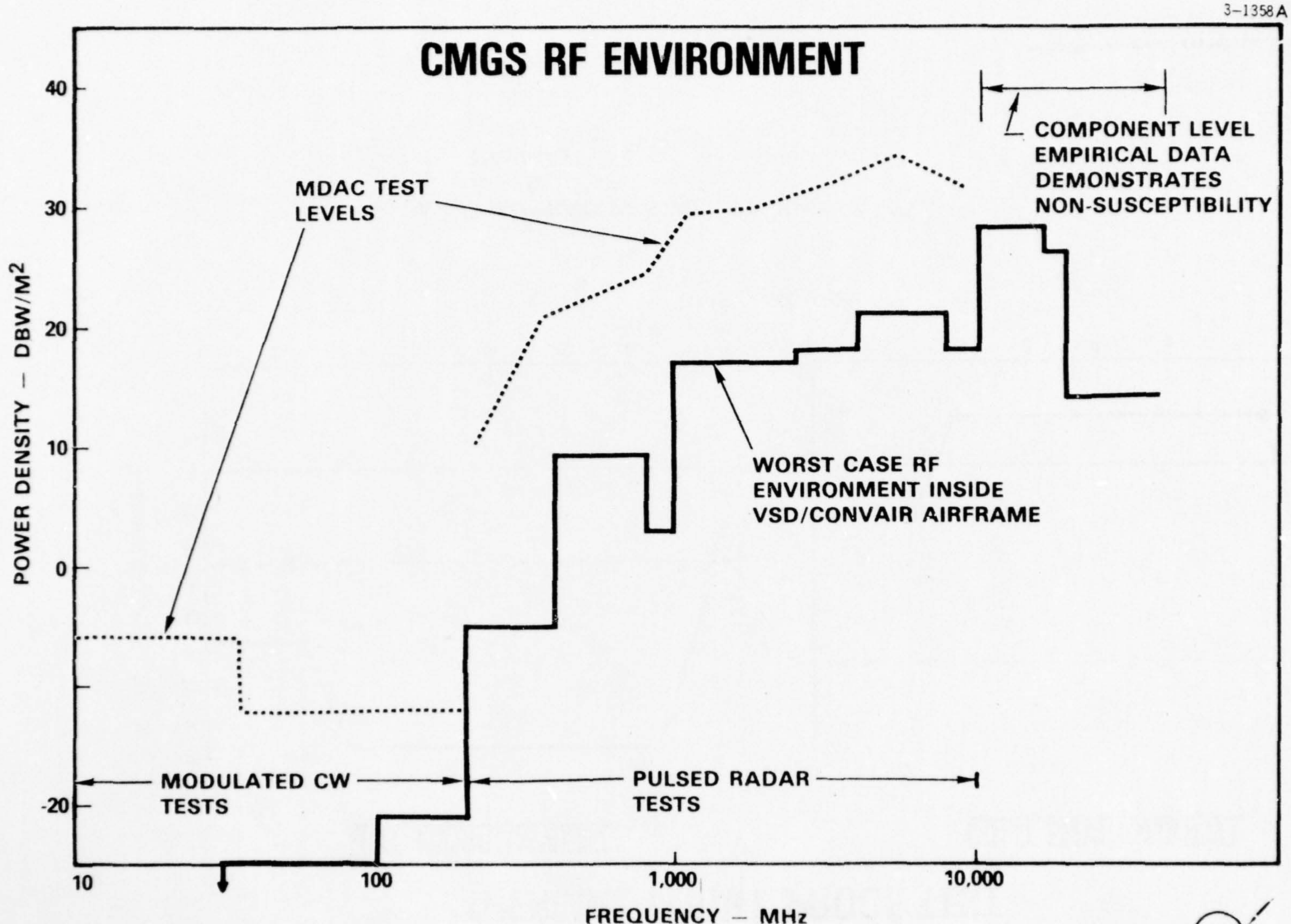
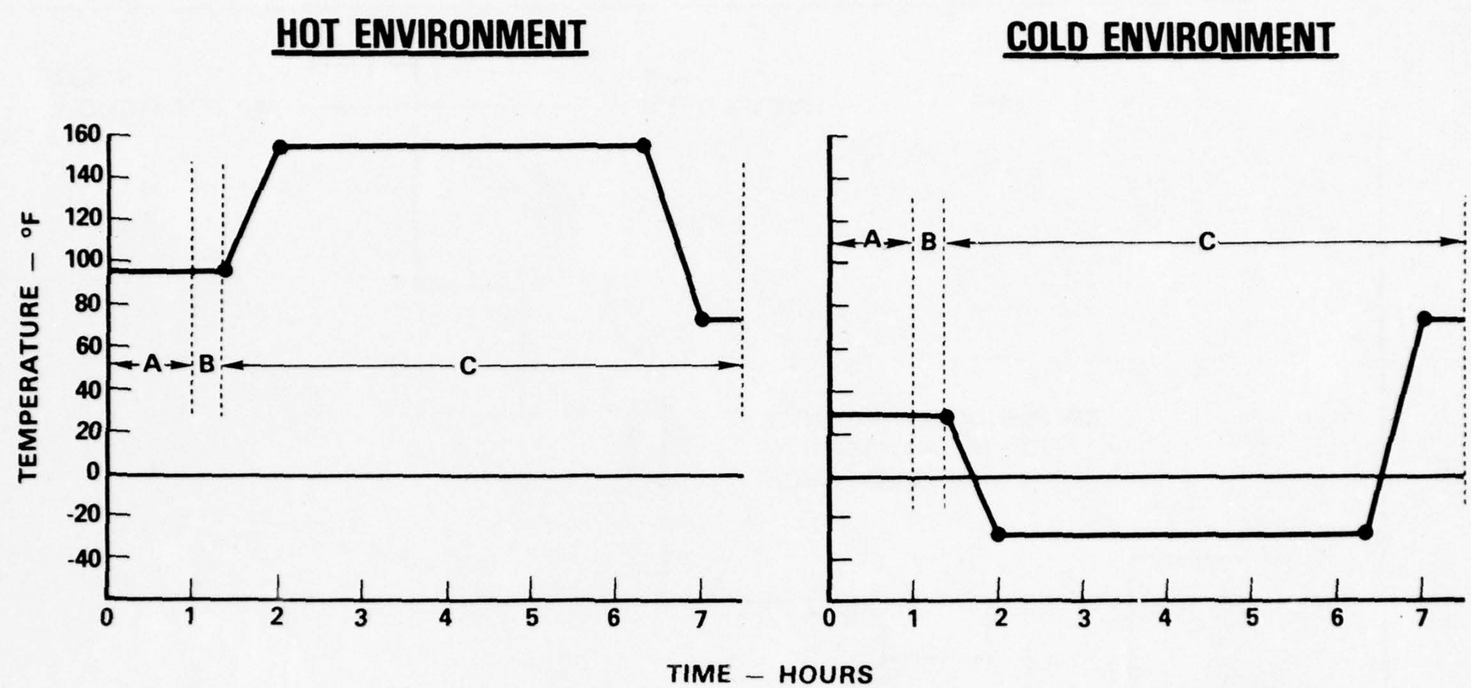


MCDONNELL DOUGLAS CORPORATION

3-1336

CMGS NAVIGATES WITHIN SPECIFICATIONS OVER THERMAL EXTREMES THERMAL FLIGHT PROOF TEST



A — TEMPERATURE STABILIZATION
B — ALIGN
C — NAVIGATE

MCDONNELL DOUGLAS CORPORATION

3-1522

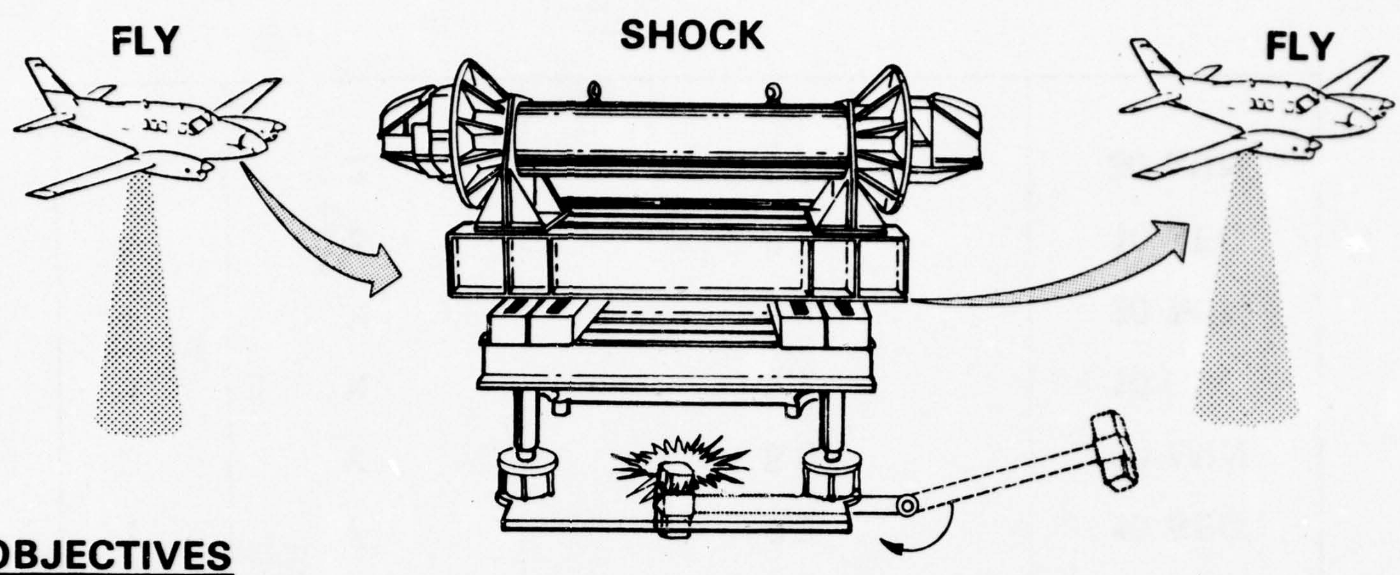
RANDOM VIBRATION
FLIGHT PROOF TEST PLAN

TEST	CMGS AXIS	VIBRATION LEVEL g RMS	DURATION
1	Y	9.2	10 SEC
2	Y	5.8	30 MIN
3	X	9.2	10 SEC
4	X	5.8	30 MIN
5	Z	9.2	10 SEC
6	Z	5.8	30 MIN

MCDONNELL DOUGLAS CORPORATION

3-1326

CRUISE MISSILE GUIDANCE SET MEETS GRADE A SHOCK



OBJECTIVES

- DEMONSTRATE SHOCK THRESHOLD (SURVIVE INTACT)*
- DEMONSTRATE SHOCK GOAL (SURVIVE OPERATIONAL)**
- DEMONSTRATE POTENTIAL FOR PASSING FLOATING SHOCK PLATFORM TESTS WHEN INSTALLED IN CRUISE MISSILE AIRFRAME
- ASSESS RELIABILITY & MAINTAINABILITY

TEST COMPLETELY SUCCESSFUL

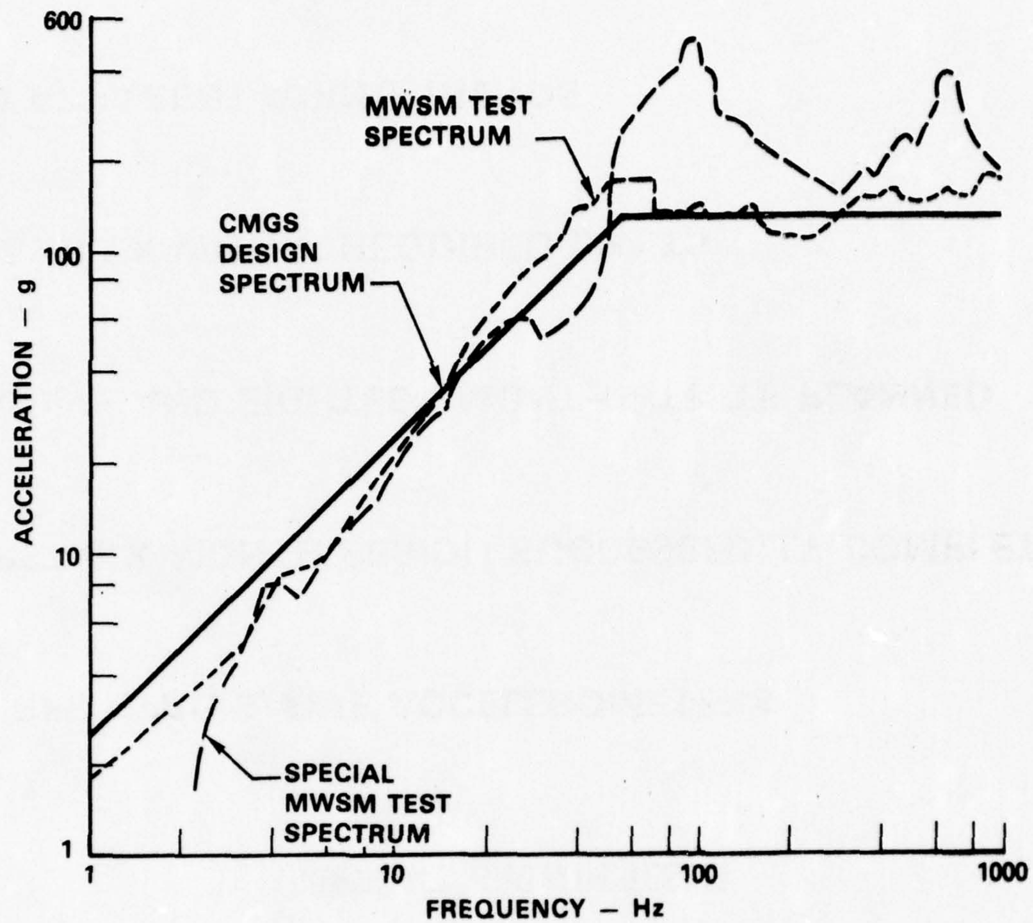
* GRADE B
**GRADE A

} MIL-S-901C

MCDONNELL DOUGLAS CORPORATION

3-1515

CMGS SHOCK SPECTRA COMPARISONS



MCDONNELL DOUGLAS CORPORATION

CMGS INERTIAL INSTRUMENT STORAGE TEST

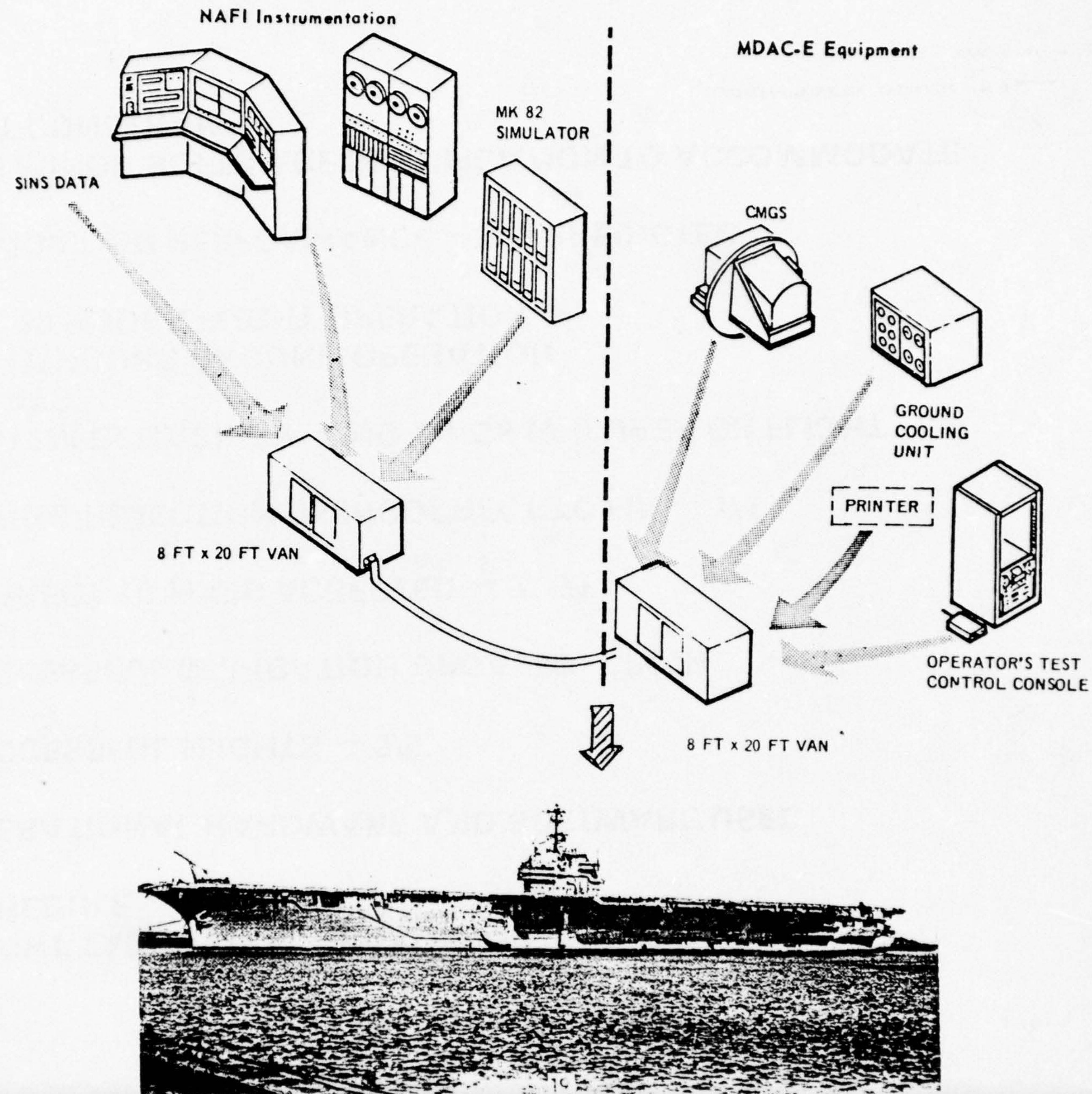
(SUPPORTS GROWTH TESTS)

- THREE GYRO'S, FIVE ACCELEROMETERS
- FIRST SIX MONTH PERIOD SUCCESSFULLY COMPLETED
- TWELVE AND EIGHTEEN MONTHS TESTS PLANNED
- ALL DATA WITHIN REQUIRED LIMITS
- NO APPARENT AGING TRENDS

MCDONNELL DOUGLAS CORPORATION

MAJOR EQUIPMENT FOR MOVING BASE ALIGNMENT TEST

3-342



3-1497

C141 FLIGHT TEST SUMMARY

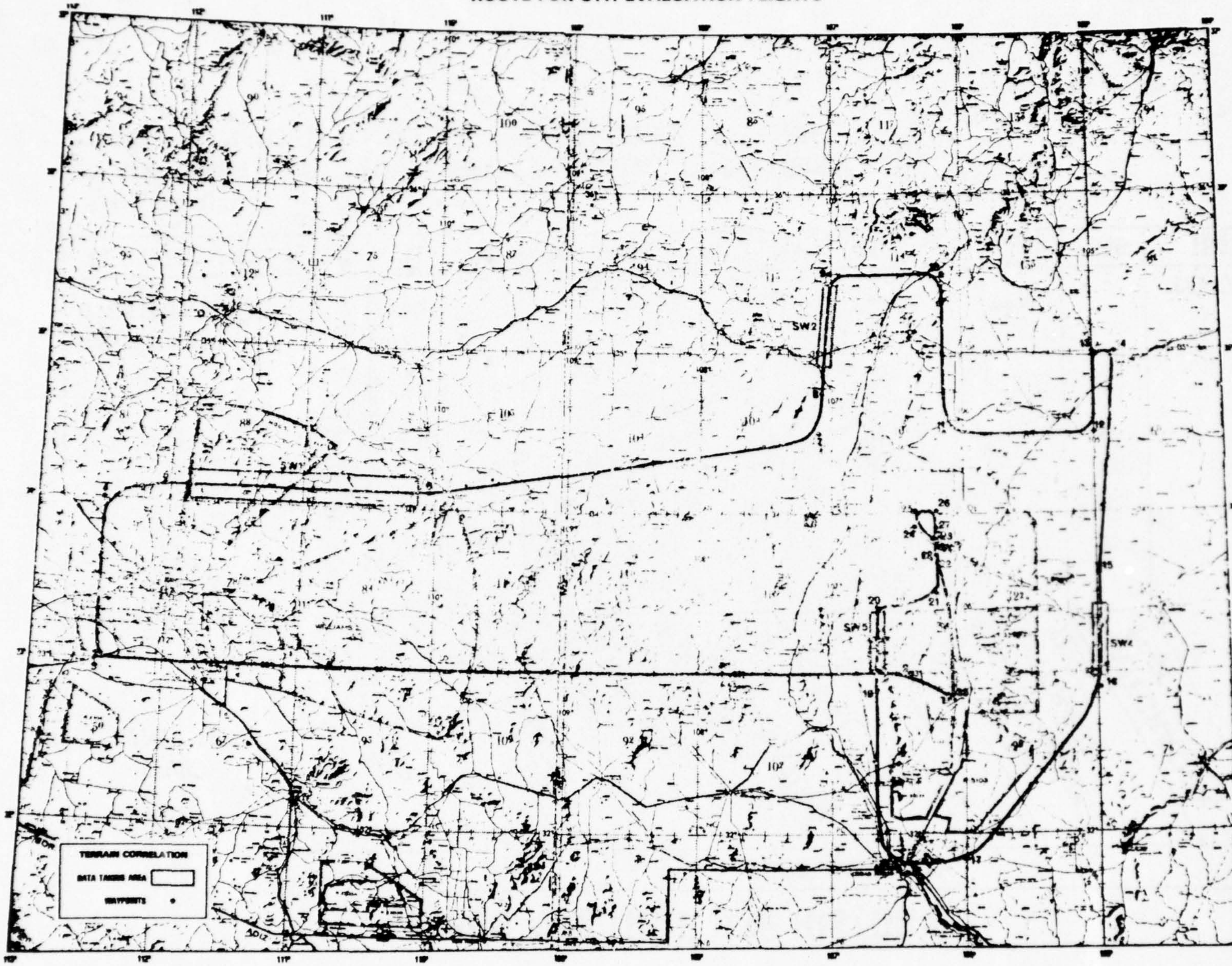
- FLIGHT TAPE AND ALL HARDWARE DELIVERED ON SCHEDULE
- OPERATIONAL HARDWARE AND SOFTWARE USED
- SUCCESSFUL FLIGHTS — 5/5
- SUCCESSFUL NAVIGATION UPDATES — 24/24
- CORRECT TC FIXES ACCEPTED — 71/71
- VOTING REJECTION OF INCORRECT TC FIX — 1/1
- SYSTEM RELIABILITY — NO CMGS FAILURES OR FLIGHT DELAYS
  - 111HOURS GROUND OPERATION
  - 33 HOURS FLIGHT OPERATION
- NAVIGATION PERFORMANCE — AS PREDICTED
- ONE MINOR SOFTWARE MODIFICATION TO ACCOMMODATE TEST CONSTRAINT

MCDONNELL DOUGLAS CORPORATION

UNCLASSIFIED

3-1499

ROUTE FOR C141 EVALUATION FLIGHTS



UNCLASSIFIED

MCDONNELL DOUGLAS CORPORATION

3-1392 B

CMGS MULTIPLE USE HISTORY

CMGS UNIT NO.	QUEEN AIR FLIGHTS	C-141 FLIGHT TEST	FLY SHOCK FLY	AT SEA ALIGNMENT	MK 82 INTERFACE	TEMPERATURE TEST	VIBRATION TEST	EMC TEST	SOFTWARE DEVELOPMENT	STORAGE TEST	INTEGRATION TEST	TOTAL
1									X			
2	X	X		*X				X			X	
3	X			X	X						X	
4	X		X				X				X	
5	X						*X	X			X	
6						X		X			X	
INERTIAL INSTRUMENTS										**X		
TEST HOURS	176	33	26	90	50	20	58	48	***800	***5000	1046	1547

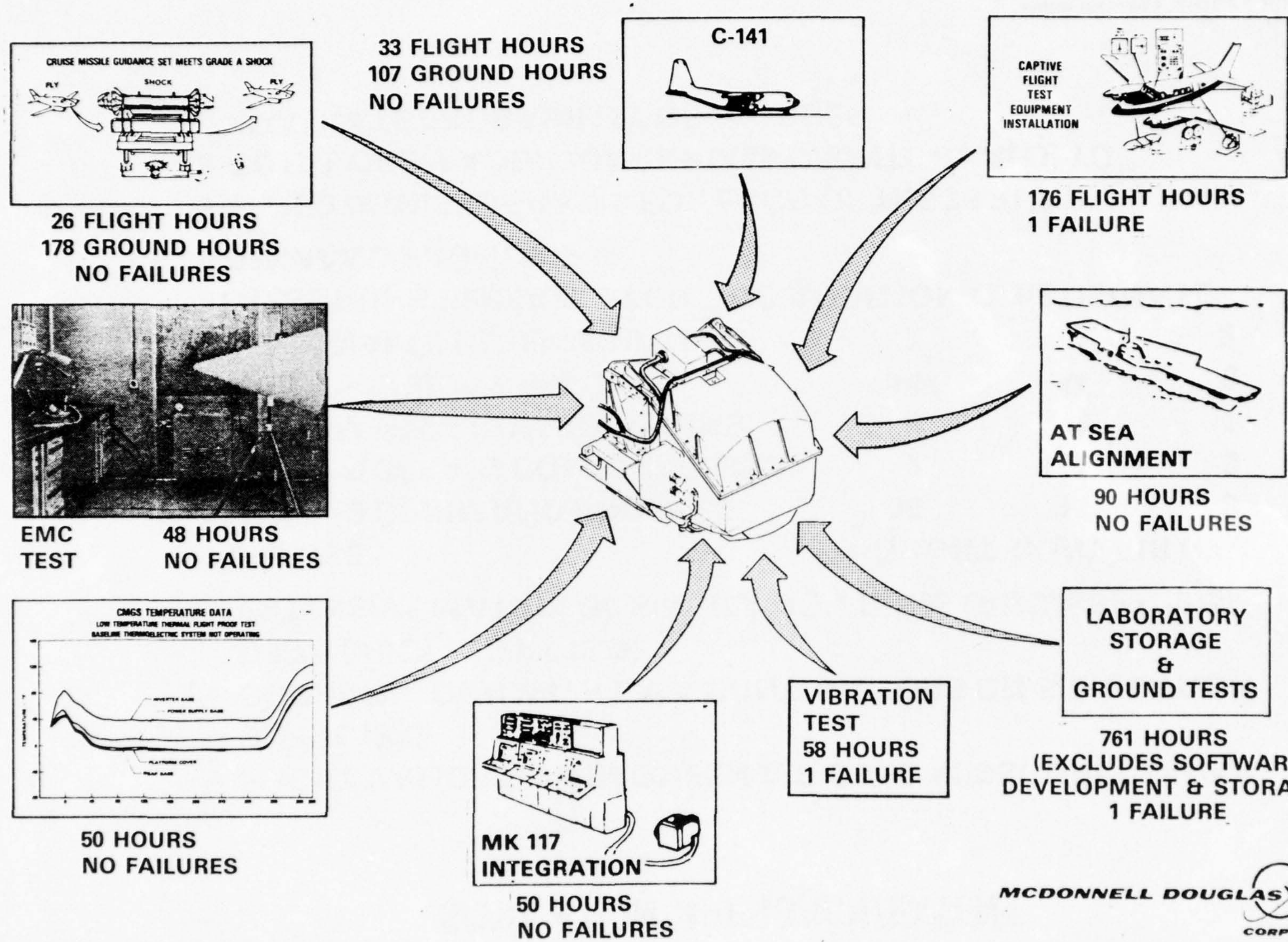
(The header "TEST ACTIVITY" spans the columns from QUEEN AIR FLIGHTS to INTEGRATION TEST.)

* BACK-UP
**SIX MONTHS STORAGE SUCCESSFULLY COMPLETED
***NOT INCLUDED IN TOTAL SYSTEM OPERATE TIME.

MCDONNELL DOUGLAS CORPORATION

3-1504

RELIABILITY RESULTS TO DATE



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3-1370

SIMULATION APPROACH/EXTENT

- FLIGHT VALIDATION IN QUEEN AIR OVER MISSOURI OZARKS (APRIL 1975)
- COORDINATION WITH CMA CONTRACTORS ON SIMULATION DATA (JULY – SEPT 1975)
- EXTENSIVE MATRIX OF SIMULATION RUNS (AUG/SEPT 1975)

PURPOSE	VOUGHT	CONVAIR	GTV
OPTIMIZE COMMAND PROFILES	16	16	8
WEIGHT/TERRAIN COMBINATIONS*	7	7	3
SEA SKIMMING COMBINATIONS	4	4	1
RADAR VISIBILITY MATRIX*	14	14	6
FUEL PENALTY DETERMINATION*	7	7	3

*THESE RUNS REPEATED FOR TWO ADDITIONAL ALTERNATE COMMAND PROFILES

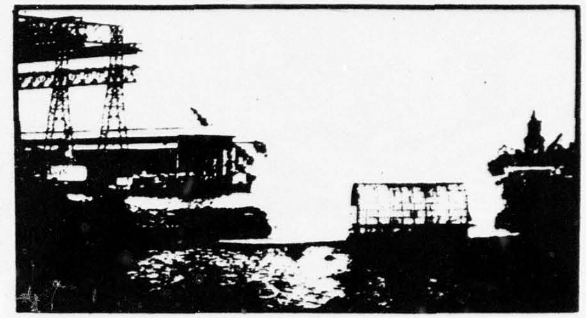
- 20 PLOTS/HISTOGRAMS FOR *EACH* OF THESE RUNS!
- TOTAL OF 277 ADDITIONAL RUNS (MONTE CARLO) TO EVALUATE PROBABILITY OF CLOBBER

MCDONNELL DOUGLAS CORPORATION

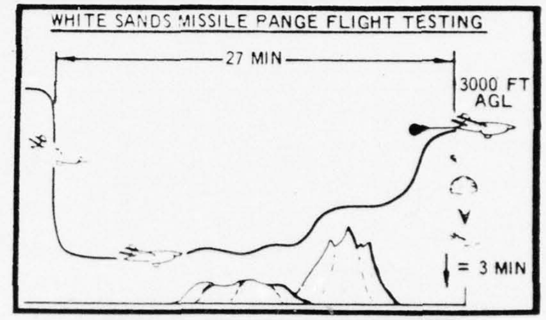
3–1359

CMGS IS READY FOR SIS ACTIVITIES

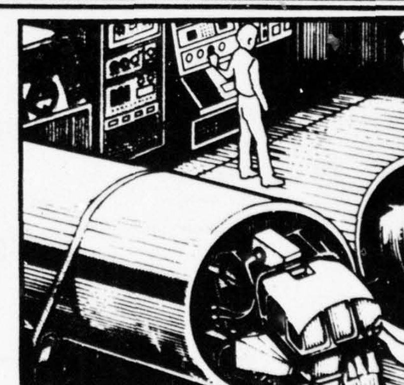
BARGE TESTS
- SHOCK VALIDATED IN CDS
- TWO CMGS AVAILABLE



GTV TESTS (MODIFIED DRONE)
- FIRST GTV READY
- SECOND GTV 1 JANUARY
- THREE CMGS READY



CMA INTEGRATION
- SIMULATION EVALUATION IN PROCESS
- CMGS HARDWARE IS AVAILABLE
- SIMULATION FACILITY OPERATING



MCDONNELL DOUGLAS CORPORATION

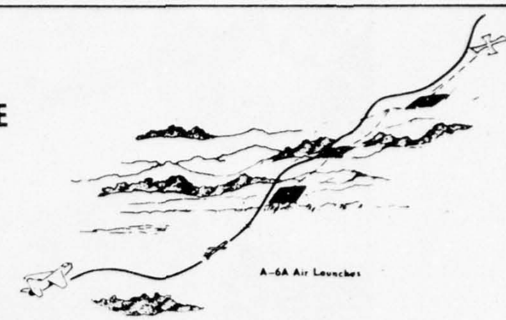
3–1360

CMGS IS READY FOR SIS ACTIVITIES (Continued)

CRUISE MISSILE FLIGHT TESTS

- FULL RANGE MISSION—NAVIGATION ACCURACY
- TERRAIN CORRELATION — TERRAIN AVOIDANCE

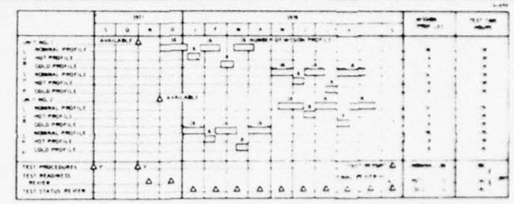
CRUISE MISSILE TEST & EVALUATION



RELIABILITY IMPROVEMENT TESTING

- GYRO & ACCELEROMETER STORAGE TEST
- STORAGE TEST OPTION
- RELIABILITY GROWTH TEST OPTION
  - DYNAMIC ENVIRONMENT

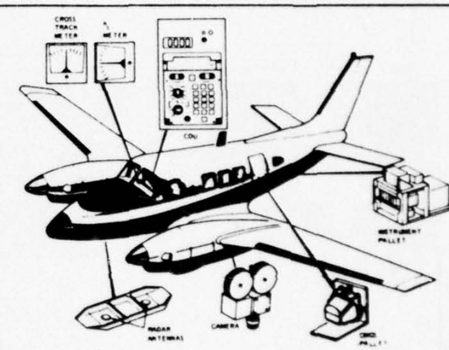
RELIABILITY GROWTH TESTING



QUEEN AIR FLIGHTS

- DEMONSTRATE DIGITAL MAP ACCURACY AND VARIATIONS
- FLY PRECISELY CONTROLLED TRAJECTORIES OVER OPERATIONAL TYPES OF TERRAIN
- REFINE DIGITAL MAP SELECTION APPROACH
- SELECT AREAS FOR ADDITIONAL TC TESTING

CAPTIVE FLIGHT TEST EQUIPMENT INSTALLATION



MCDONNELL DOUGLAS CORPORATION

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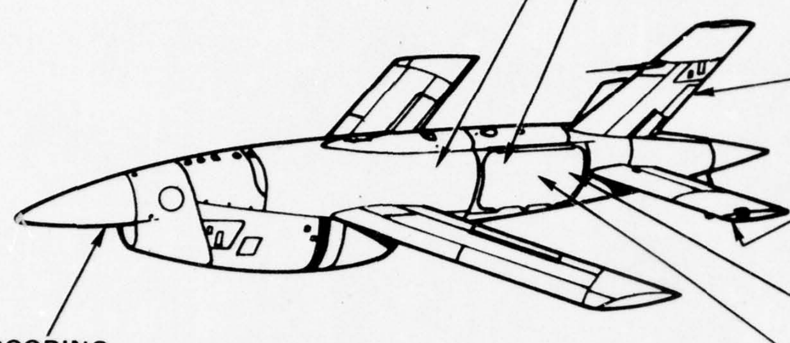
BQM-34A MODIFICATIONS FOR GTV FLIGHTS

- MODIFIED BY LEAR SIEGLER INC. UNDER SUBCONTRACT



- MODIFICATION OF FIRST GTV IS COMPLETE
- SECOND & THIRD GTV MODS IN WORK
- FOURTH GTV WILL BE MODIFIED IF NEEDED
- FIFTH GTV USED FOR FLIGHT CONTROL SIMULATIONS IN LAB

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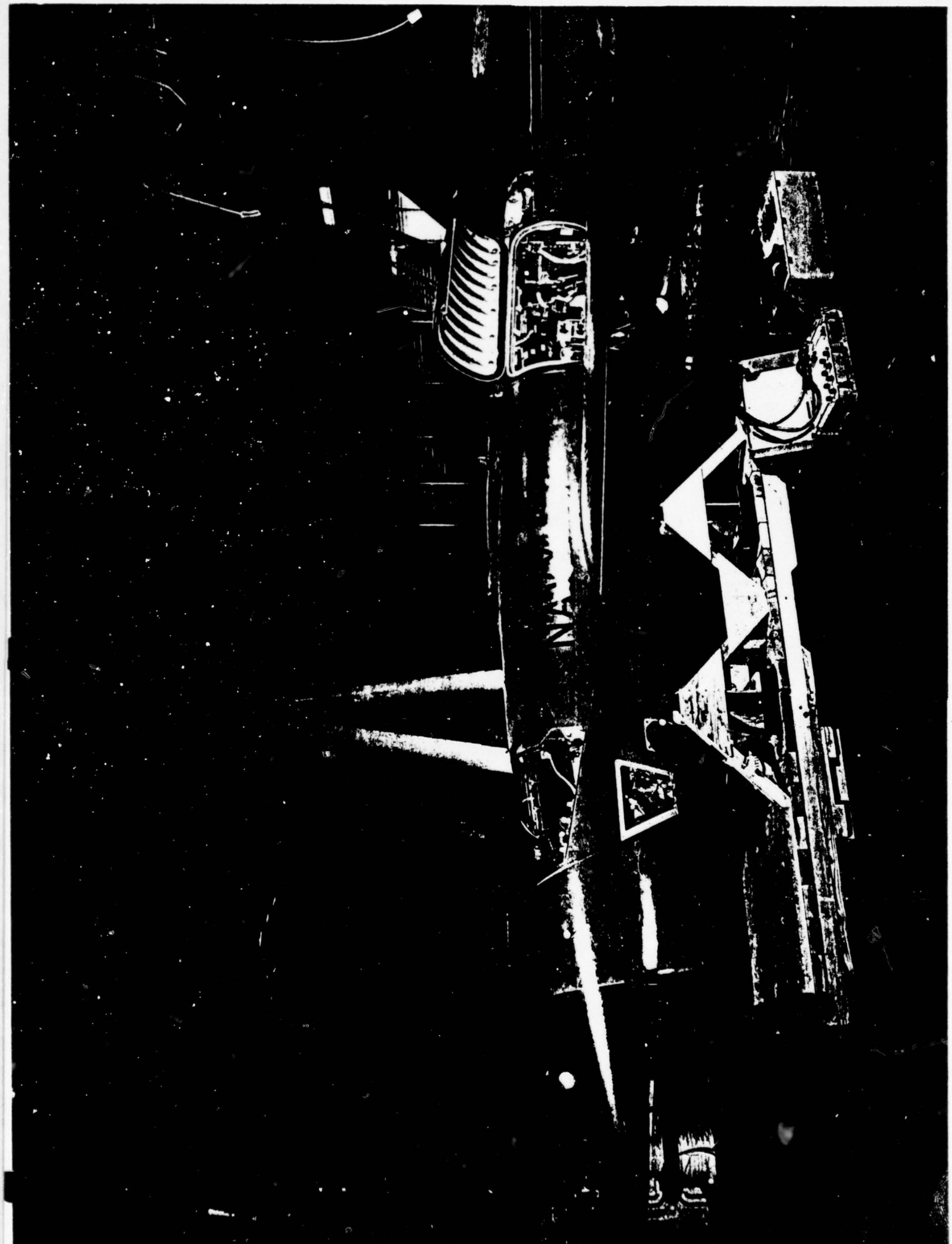

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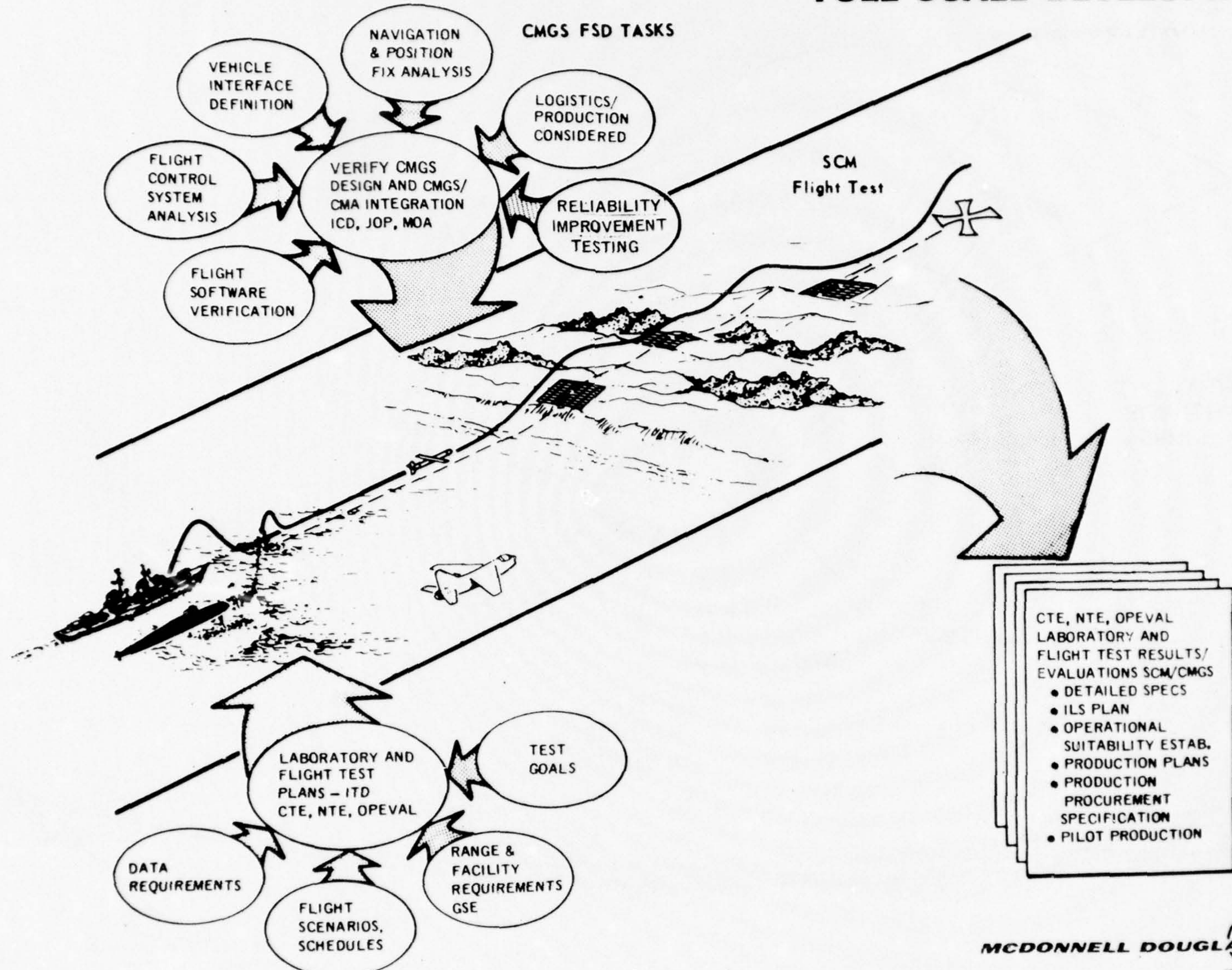
FULL SCALE DEVELOPMENT

3-1354



MCDONNELL DOUGLAS CORPORATION

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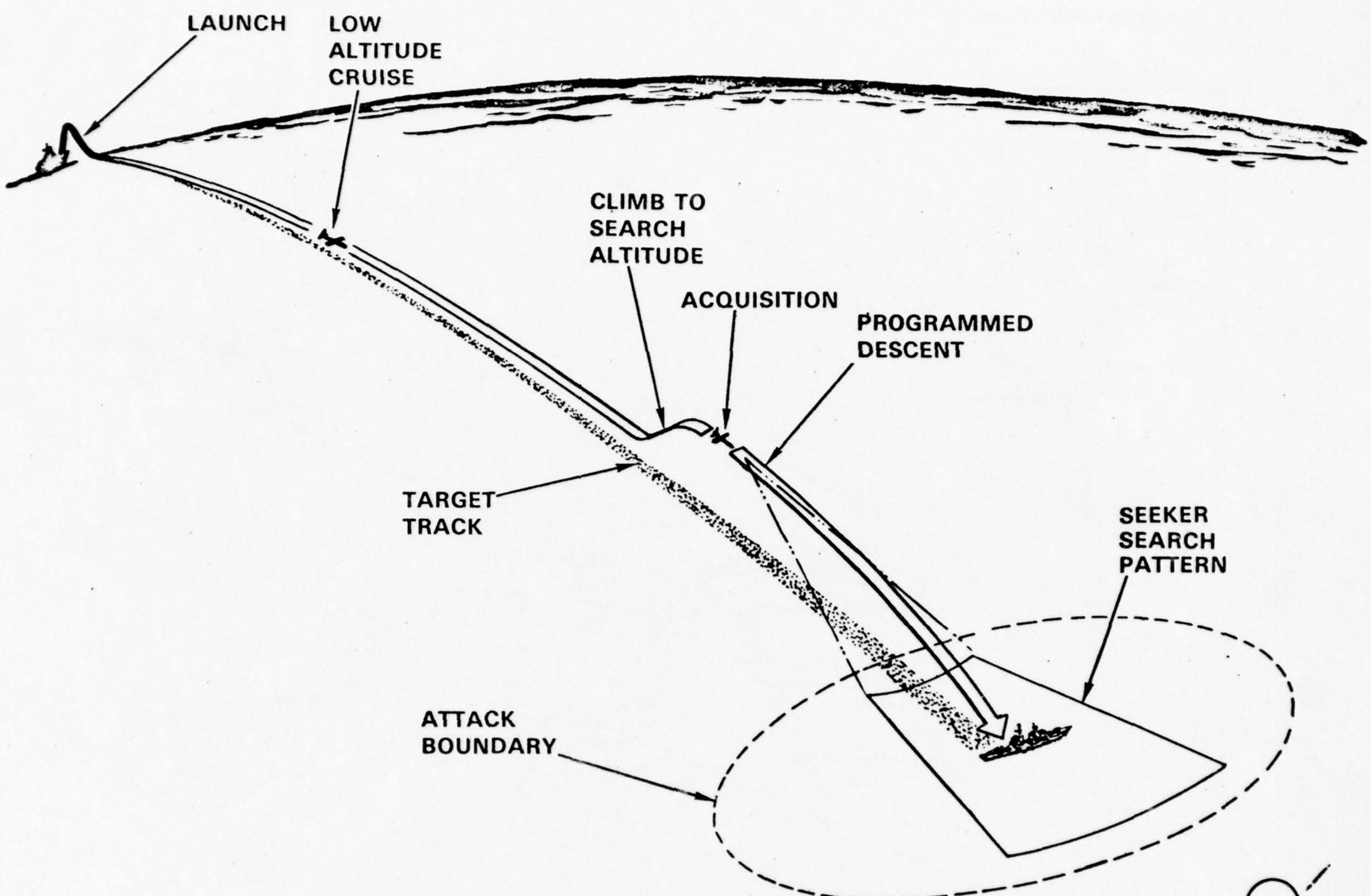
3-1544

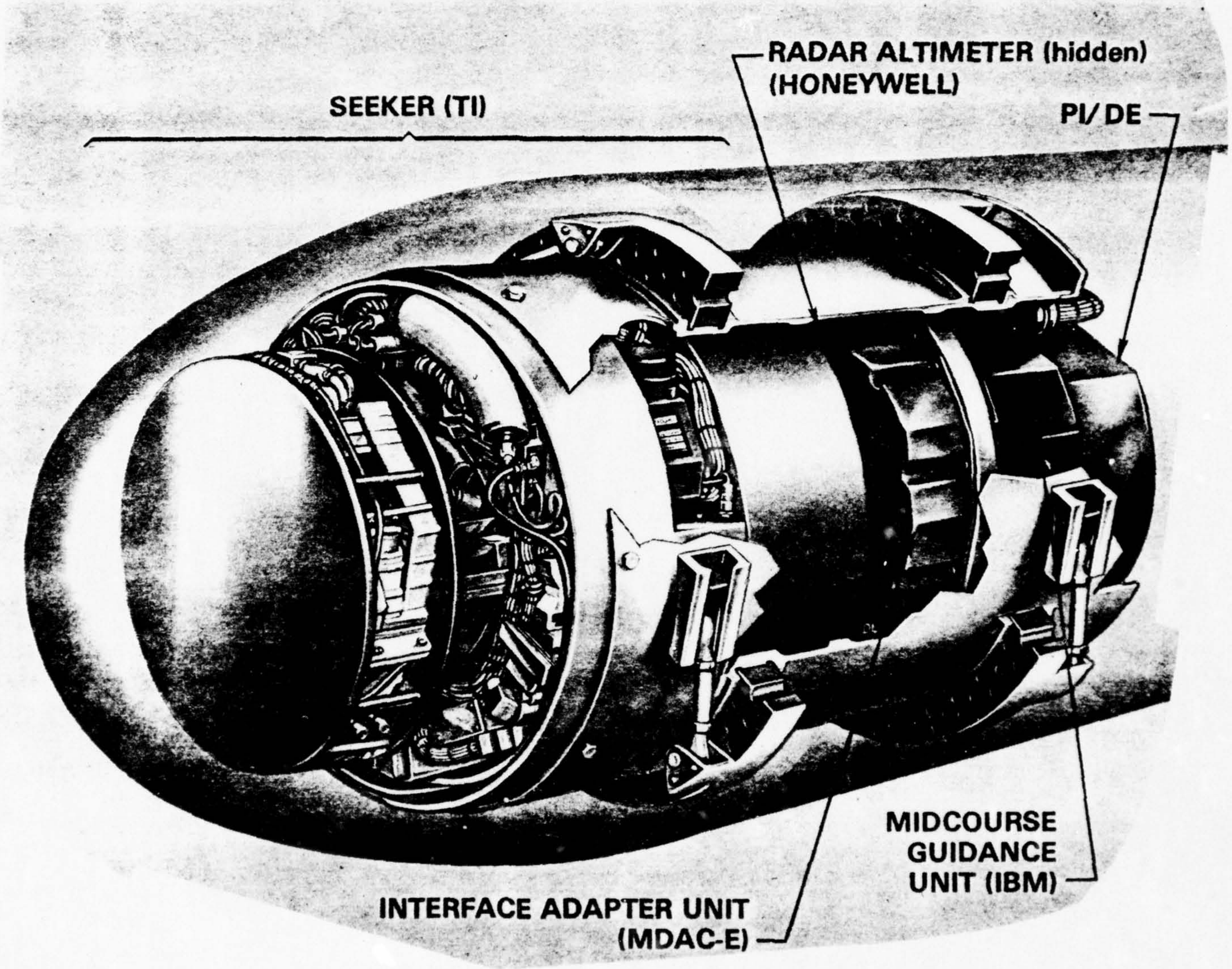
TACTICAL TOMAHAWK MISSION



MCDONNELL DOUGLAS CORPORATION

UNCLASSIFIED

TACTICAL TOMAHAWK GUIDANCE SET



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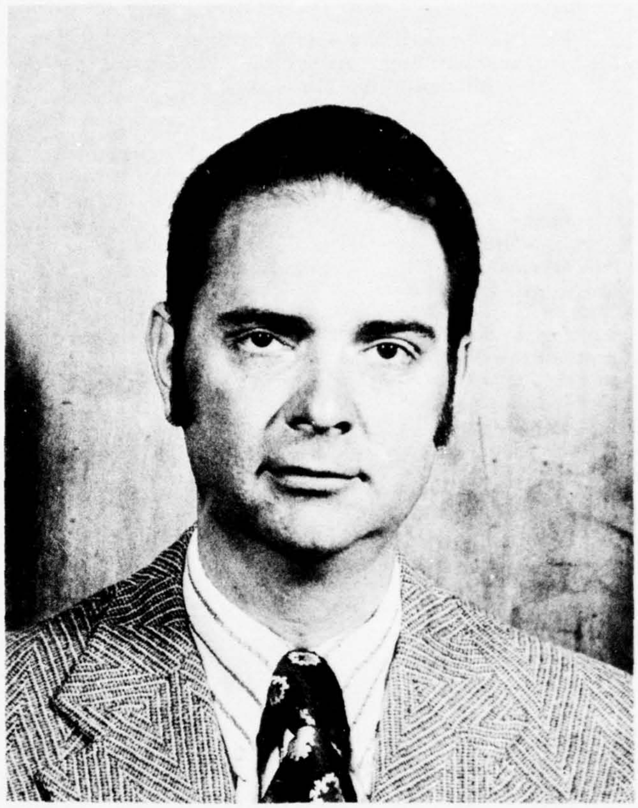
BRIEFING TITLE

LASER GYRO NAV SYSTEM



PAUL G. SAVAGE

Paul G. Savage is currently Technical Director for the Honeywell/Navy Ring Laser Gyro Navigator Advanced Development Program, and was previously in charge of the Honeywell Laser Inertial Navigation System Program that recently completed successful flight tests at Holloman AFB. Since joining Honeywell in 1963 he has had major responsibilities in the design and development of Advanced Guidance Navigation and Control Systems for aircraft and missiles. Prior to joining Honeywell, Mr Savage was employed at Lockheed Missiles and Space Corporation where he was engaged in Advanced Control Systems Design for sattelite application. He received his BS and MS in Aeronautical Engineering at MIT.

HONEYWELL LASER INERTIAL NAVIGATION SYSTEM (LINS)
TEST RESULTS

Paul G. Savage and Mario B. Ignagni
Honeywell Government and Aeronautical Products Division
Minneapolis, Minnesota

ABSTRACT

This paper describes the Honeywell Laser Inertial Navigation System (LINS) and presents results of 1975 laboratory, road, and Holloman flight tests performed with LINS engineering hardware. The basic sensing elements of the LINS are Honeywell GG1300 laser gyros. Advantages of LINS compared to conventional inertial navigation systems are faster reaction time and lower procurement/maintenance costs. A LINS engineering system was road tested at Honeywell and then flight tested at Holloman Air Force Base during May-June 1975 in a C-141 aircraft. System performance at Holloman was 0.7 nmi/h CEP (based on the Navy CAINS formula) for 13 test flights (82 aircraft navigation hours and 65 flight hours) without any temperature controls or optical alignments. Each flight run was from a cold start with 10 minutes warm-up and 10 minutes alignment. Over 268 hours were accumulated on the system during its test period at Holloman without any failures, recalibrations, or aborted tests.

INTRODUCTION

Major breakthroughs have occurred over the last three years in laser gyro technology. Two orders of magnitude performance improvement and the elimination of lifetime problems now make the laser gyro a prime contender as the strapdown inertial sensor for the next decade. Performance data on the Honeywell GG1300 laser gyro has demonstrated long-term repeatability better than 0.01 to 0.02 deg/h consistent with 1 to 2 nmi/h inertial navigation requirements. The ability to achieve these performance levels without thermal controls provides the potential for a 2 to 3 minute reaction time (warm-up and alignment) for production inertial systems using laser gyros. (Three to five minute reaction times from a cold start with 1 1/2 nmi/h performance have already been demonstrated in the laboratory with LINS engineering hardware.) This is an important performance advantage in military applications requiring fast response (e.g., Navy carrier aircraft operations). Most significantly, the acquisition and life cycle costs for laser gyro inertial navigation systems promise to be appreciably lower than for conventional gimbaled navigators due to the elimination of mechanical gimbals, increased ruggedness, and improved reliability.

Recognizing the potential for the laser gyro in strapdown inertial systems, Honeywell in the second half of 1971 initiated an in-house program to develop an aircraft strapdown navigation system to use this new sensor. Laser Inertial Navigation System (LINS) is the Honeywell acronym for the class of navigation systems developed under this program.

A set of LINS engineering hardware was developed in 1975 for road and flight test evaluation purposes. This paper describes the Honeywell LINS engineering hardware, relating these to projected LINS production configurations. Laboratory, road, and Holloman flight tests performed with the LINS engineering system are described and test data presented illustrating positioning and velocity accuracy capabilities.

BASIC LINS CONFIGURATION

The basic elements used in the Honeywell Laser Inertial Navigation System (LINS) are a set of strapdown laser angular rate sensors (gyros), a set of strapdown accelerometers, and a navigation computer (Figure 1).

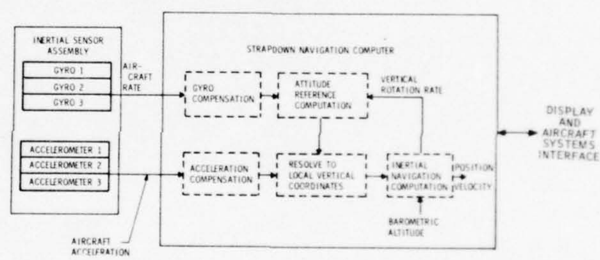


Figure 1. Basic LINS Functional Block Diagram

The laser gyros and accelerometers provide precision roll/pitch/yaw axis rate and acceleration signals to the navigation computer where they are compensated for known systematic errors (such as fixed bias and scale factor error). The compensated signals are used in a three-axis attitude integration algorithm to compute aircraft attitude relative to local vertical/azimuth coordinates. The angular rate of the aircraft over the surface of the earth (due to earth's rotation and aircraft velocity) is included in this computation to account for the rotation of the local vertical.

The aircraft attitude data is used to resolve the roll/pitch/yaw aircraft axis acceleration vector data into the local vertical/azimuth coordinate frame. The computed horizontal/vertical acceleration components are then integrated in an inertial velocity/position algorithm to calculate aircraft horizontal velocity and latitude/longitude position. Barometric altitude is used in the inertial computation to stabilize the vertical channel.

LINS INERTIAL SENSORS

GG1300 Laser Gyro -- The baseline gyro for LINS is the Honeywell GG1300 laser gyro (Figure 2).

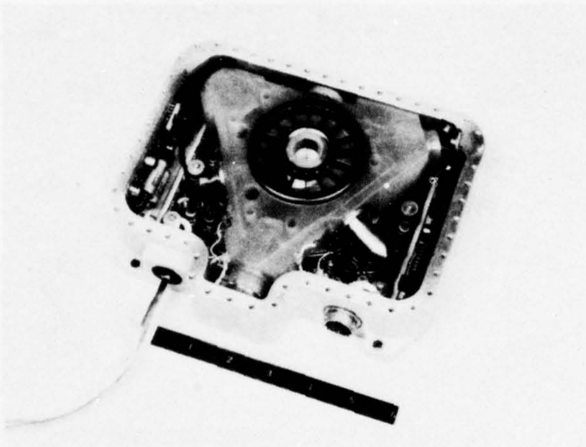


Figure 2. GG1300 Laser Gyro

Performance characteristics of today's GG1300 technology are:

- High accuracy (0.01 deg/h bias, 0.0005 percent scale factor error, 0.005 deg/$h^{1/2}$ random walk).
- Fast reaction time (no heaters or warm-up requirement).
- Long-term stability (no preflight calibration).
- Fine resolution (1.57 arc seconds pulse size over the full operating range (-400 to +400 deg/s).
- G-insensitive performance.
- High reliability (few assembly parts and no moving parts).

Systron Donner 4841 Accelerometer -- The baseline accelerometer for LINS is the Systron Donner Model 4841 accelerometer (Figure 3).

The 4841 is a low-cost inertial grade electrically servoed accelerometer designed for strapdown applications in aircraft and missiles. Some of the significant features of the 4841 include:

- High accuracy (100 ug bias stability, 0.05 percent scale factor accuracy) over wide temperature range (-65°F to 160°F) without heaters.
- Fast reaction time (30 seconds).

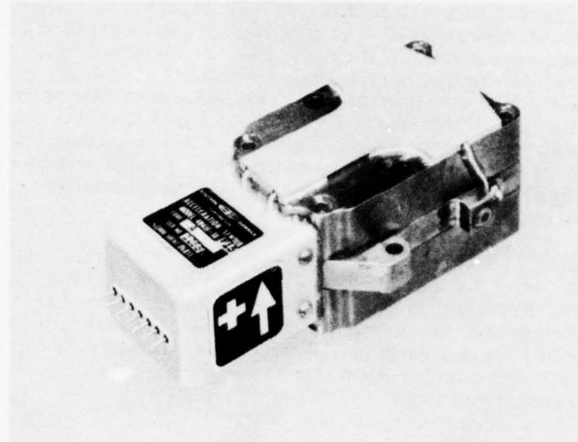


Figure 3. Systron Donner 4841 Accelerometer

Figure 4 is an artist's conception of a production LINS navigation unit configuration. The navigation unit, packaged in a standard full long ATR case, houses a three-axis inertial sensor assembly (laser gyros and accelerometers), the system computer, system power supply, and external I/O for interfacing with other aircraft systems. The functional operation of this system would be as depicted in Figure 1. The navigation unit in conjunction with a mode select panel and a control display unit would constitute a complete LINS navigation system that is functionally equivalent to the gimbaled inertial navigation systems currently in use on today's military aircraft.

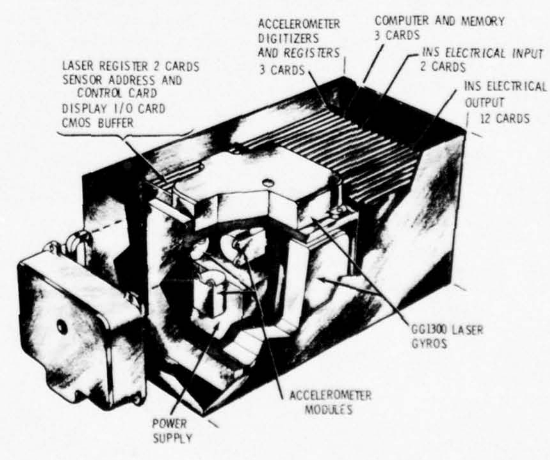


Figure 4. Projected LINS Navigation Unit

Figure 5 is a block diagram illustrating the functional operation of a projected skewed redundant fail-operational/fail-safe LINS production configuration (compare with Figure 1 for the non-redundant configuration). The system is composed of a hexad (six-axis) sensor array and triple-redundant computers. The hexad array is formed from three identical ISA's (inertial sensor assemblies), each containing two gyro/accelerometer pairs.

Each ISA shares a common power supply with one of the computers and has its data transmission synchronized to that computer. The three computers are synchronized together by a clock intercom between each computer. The two angular rate and acceleration signals from each ISA are transmitted to all computers.

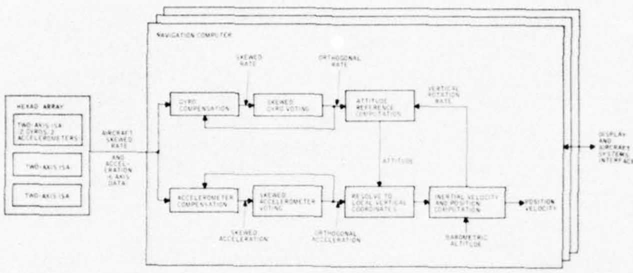


Figure 5. Skewed Redundant LINS Block Diagram

The orientation of the input axes of one of the gyro/accelerometer pairs in each inertial sensor assembly box (two-axis ISA), as shown in Figure 6, is parallel to the long axis of the ISA (normal to the front face). The second gyro/accelerometer set is mounted with input axes perpendicular to the first set but skewed (nonorthogonal) relative to the ISA base.

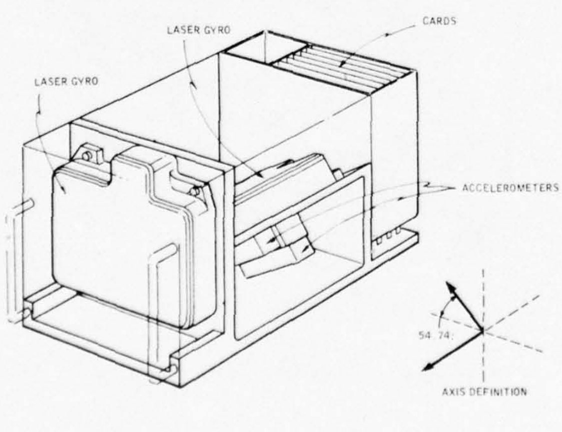


Figure 6. Two-Axis ISA

The three two-axis ISA's are mounted to a common base (Figure 7), which is part of the aircraft rack structure, in precision alignment such that the long axes of the boxes are skewed relative to one another.

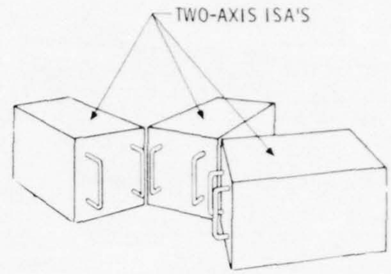


Figure 7. HEXAD Mounting Arrangement

Each of the three sets of two ISA's in Figure 7 define a four-axis (tetrad) gyro/accelerometer sensor array. With the ISA's oriented as in Figure 7, the four input axes for each tetrad are non-coplanar (i. e., do not lie in a single plane). Under these conditions, software routines in each computer can operate on any one of the three tetrad signal sets to analytically calculate the equivalent roll, pitch, and yaw axis rate/acceleration data for computer operations. In addition, for each tetrad, three of the four gyro/accelerometer signals can be combined to analytically derive the fourth gyro/accelerometer inputs. If the derived input signals are unequal to the measured fourth gyro/accelerometer outputs (within prescribed tolerances), a failure in one of the tetrad sensors is indicated.

This logic provides the capability for assessing the functional integrity of each of the three tetrads. A single failure in the hexad (i. e., in one of the two-axis ISA's) will cause two tetrads to exhibit failures. The third tetrad will not exhibit failure, thereby isolating the failed ISA box to the unit not included in the functioning tetrad. Under these conditions, the identified functioning tetrad would be used to derive the roll/pitch/yaw axis data in the computer, thus allowing proper system operation with one failure (single fail-operational). Multiple failure occurrences can also be identified by this approach, but without a corresponding failure isolation. Under these conditions, the computer can be shut down safely (fail-safe) and the pilot notified of the shutdown by the appropriate failure panel status lamp. Thus, the hexad geometry provides a single fail-operational/fail-safe sensor capability. The triple-redundant computer configuration used with the hexad array is consistent with this redundancy level. A tetrad (2 two-axis ISA's) with a dual-redundant computer would provide a fail-safe capability.

LINS ENGINEERING HARDWARE

The LINS engineering hardware developed for tests in 1975 is designed for assessing system performance with both nonredundant and skewed redundant sensor operation. Sufficient flexibility has been included in the hardware design for special aircraft interface requirements and software program development. Figure 8 defines the black-box assemblies that comprise the engineering hardware configuration. The hardware consists of an inertial sensor assembly (ISA), a strapdown navigation computer (SNC), separate alterable memory units for the computer, a control/display unit (CDU), a computer control unit (CCU), and a non-interruptable power supply that enables system operation through aircraft power switchover transients from standby to primary power.

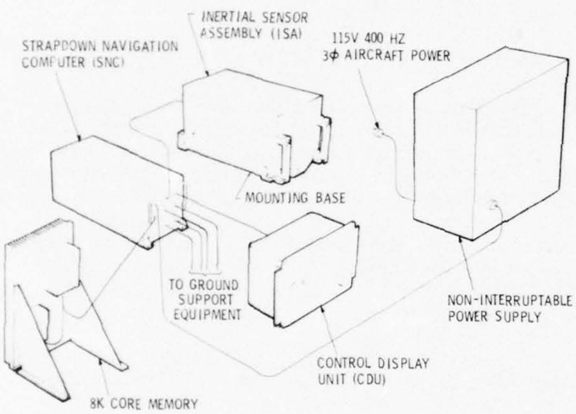


Figure 8. LINS Engineering Hardware

The ISA (Figure 9) contains three strapdown accelerometers and four laser gyros (three orthogonal, one on the bottom side of the ISA, and a fourth gyro skewed relative to the other three). Because the gyros and accelerometers are thermally insensitive, the ISA is operated heaterless. Due to the low power dissipation in the ISA (50 W), ducted air cooling is not required below 130°F ambient.

The Honeywell HDC-301 metal-oxide semiconductor, large-scale integrated circuit (MOS LSIC) processor is used in the SNC to perform the arithmetic functions. The HDC-301 is a military-qualified, 16-bit parallel digital general-purpose processor with double-precision capability and basic instruction times of 3.8 μs for add and 16 μs for multiply. It is packaged on a single six-inch square multilayer plug-in card.

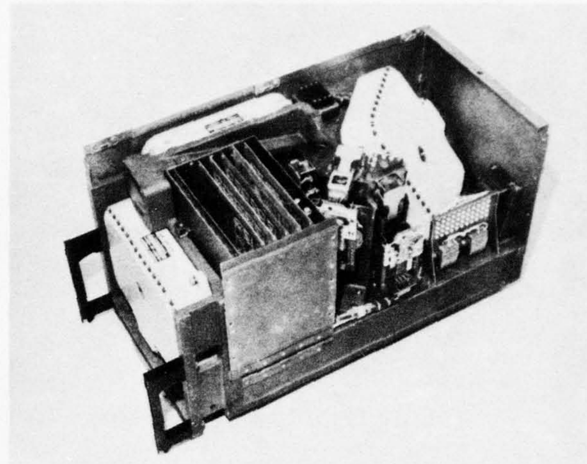


Figure 9. LINS ISA

The SNC (Figure 10) contains two HDC-301 processors (Figure 11), 8000 words of alterable core memory for each processor, an ISA interface, a CCU interface for rapid computer program changes, and a CDU interface for pilot-system communication.

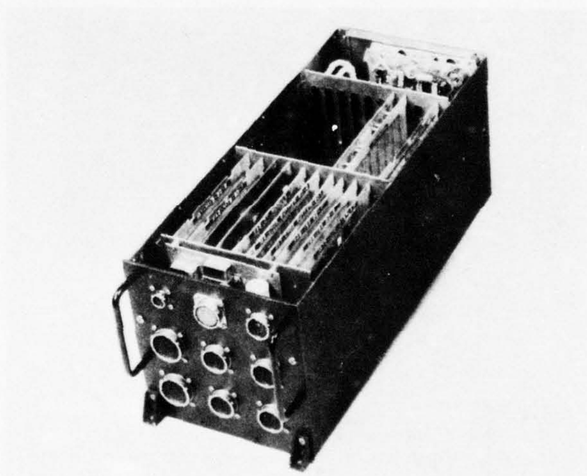


Figure 10. LINS SNC

One of the HDC-301's is used for basic skewed or nonredundant inertial calculations. The other HDC-301 will be used for experiments such as Kalman filter aiding. Growth is included in the SNC interface for the ISA to accept inputs from up to six gyros and six accelerometers. Growth provisions are included in the SNC chassis (nine plug-

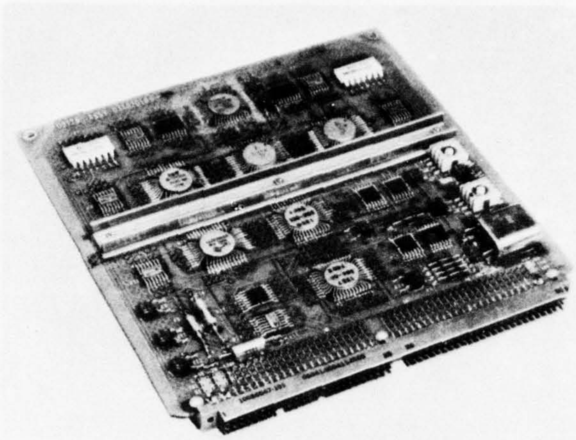


Figure 11. HDC-301 Processor

in card connectors and slots) for the addition of special input/output cards to meet particular test aircraft requirements. For the Holloman flight test in May-June 1975, an interface was included for a barometric altimeter input and a flight recorder output.

Figure 12. LINS CDU

The CDU (Figure 12) provides the capability to operate the system in its basic operating modes (standby, align, navigate) either aided or unaided, with either an orthogonal three-axis nonredundant gyro set or a skewed redundant four-gyro configuration. In the orthogonal mode, only the three orthogonal gyro signals are used in the strapdown computation and the system operates as a true nonredundant system. If the redundant mode is selected, the system uses the outputs from all four gyros, averaging the signals to obtain the best estimate for the equivalent three-axis rate signals for the strapdown computer. Only the nonredundant orthogonal triad mode was tested in May-June 1975 at Holloman. Skewed redundant and/or aided mode tests will be performed at a later date.

When in the skew redundant mode, the system is designed such that any of the four gyros can be commanded to fail through the CDU to exercise the skew redundancy failure detection/replacement capability of the system. The SNC, upon receipt of a failure command for a particular gyro from the CDU, corrupts the input signal from that gyro by software program to simulate a specified failure mode (hard or soft). The failure mode software is alterable through CCU input to the SNC memory. The SNC then operates on the altered gyro signals in the skew-redundant failure detection software (also alterable through CCU interface). Upon detecting that the failure has occurred, the failure detection software issues a discrete to the CDU to activate a failure indication light; simultaneously, the failed gyro is switched off-line and the system converted to the fail-operational mode with the remaining good gyros providing data inputs.

BASIC LINS INERTIAL SOFTWARE

The attitude update in the LINS inertial navigation software (Figure 1) incorporates a fifth-order direction cosine algorithm updated at 40 Hz to 32-bit precision in conjunction with a 160-Hz coning compensation algorithm to provide the combined equivalent of 160-Hz total attitude update rate. Compensation is included in the attitude update for computer roundoff, attitude algorithm orthonormalization, and gyro deadband, quantization, misalignment, scale factor, and bias.

The position/velocity update is based on azimuth wander geodetic vertical navigation coordinates for an all-earth capability with an ellipsoidal earth model. Altitude stabilization is accomplished with a third-order blending filter using barometric altitude input data. Compensation is included for angular rotation during acceleration transformation, accelerometer assembly size effect, and accelerometer misalignment, scale factor, and bias error.

The initial alignment algorithm is designed to derive the maximum benefit from the alignment time advantage afforded by strapdown compared to gimbaled systems, not requiring a coarse align mode to physically level the inertial reference (and eliminate g-sensitive errors) before engaging the sensitive azimuth alignment loop. Based on a Kalman estimator formulation, the alignment filter can erect to vertical and simultaneously align in azimuth in the presence of gyro/accelerometer pulse quantization noise and 0.05 ft/s aircraft acceleration noise to an accuracy of 1 arc minute (in azimuth) in less than two minutes time with no a priori knowledge of initial aircraft attitude. The attitude alignment accuracy of LINS is, thereby, limited only by instrument error (random noise and bias error in the laser gyro and bias trending in the accelerometer).

SOFTWARE TESTING

The LINS align and flight mode software programs were validated in two steps prior to system level testing. First, the HDC-301 programs were tested for accuracy and round-off error propagation by use of a software simulator. The simulator provides both the "correct" or "reference" solution for a given set of simulated gyro and accelerometer inputs and the corresponding HDC-301 solution. The reference solution is obtained from a FORTRAN analog of the attitude reference and navigation equations, and the HDC-301 solution is obtained from a FORTRAN simulation of the HDC-301 machine code (the FORTRAN simulation preserving all of the salient computational characteristics such as precision, word length, etc). While this test is extremely valuable in itself, it is limited (due to computer run-time constraints) to periods of a minute or less of simulated time.

The second step in the validation process is in principle the same as the first, with the actual flight computer substituting for the simulated HDC-301 program, using artificially set sensor inputs to simulate the sensor signals that would be measured during the specified flight profile. Here again, a FORTRAN reference solution is used as the basis of comparison, but the time over which the two solutions can be compared is extended to an hour or more. This allows much greater insight into the long-term error propagation tendencies of the attitude reference and navigation software.

LASER GYRO TESTING

During the last quarter of 1973, a life test was initiated on the newest model GG1300 laser gyro (S/N 174) to establish a performance baseline against which continued progress in laser gyro development could be judged. The data in Figure 13 is a plot of the stability measured on S/N 174 since initiation of the life test. Over 3500 operating hours have been accumulated on the gyro to date. Each data point includes at least 3 hours of gyro off time in a room temperature environment. Some data points also include thermal cycling and movement of the gyro to different test mounts. The results show that 0.01 deg/h (equivalent to 1 nmi/h system performance) long-term bias stability is achievable today with the current GG1300 design.

Similar test data (Figure 14), including accuracy measurements while under temperature and vibration exposures, was taken on the four laser gyros (Serial Numbers 9, 10, 11, 12) used in the LINS engineering hardware ISA. The data in Figure 14 depicts the bias shift of the gyros from their original calibrated values (before test initiation) for temperature ranges of 0°F to 160°F and for ±1g 20-2000 Hz continuous vibration exposure. The data shows that the laser gyro accuracy is within a ±0.02 deg/h band for all gyros, and within a 0.01 deg/h band for two of the gyros for the environmental range and duration period of the tests. On the basis of this data, Honeywell expected to demonstrate LINS navigation accuracy of 1-2 nmi/h CEP in the Holloman May-June 1975 flight tests.

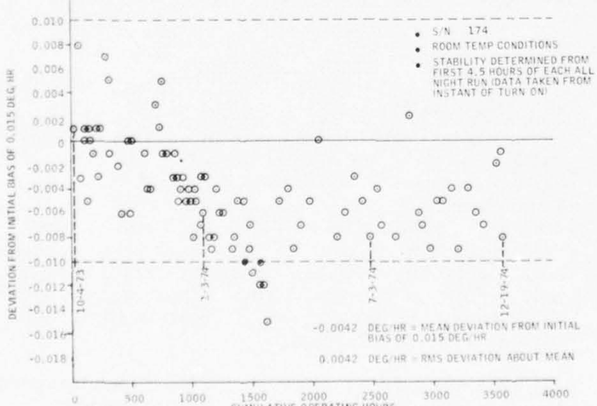


Figure 13. GG1300 Long-Term Stability

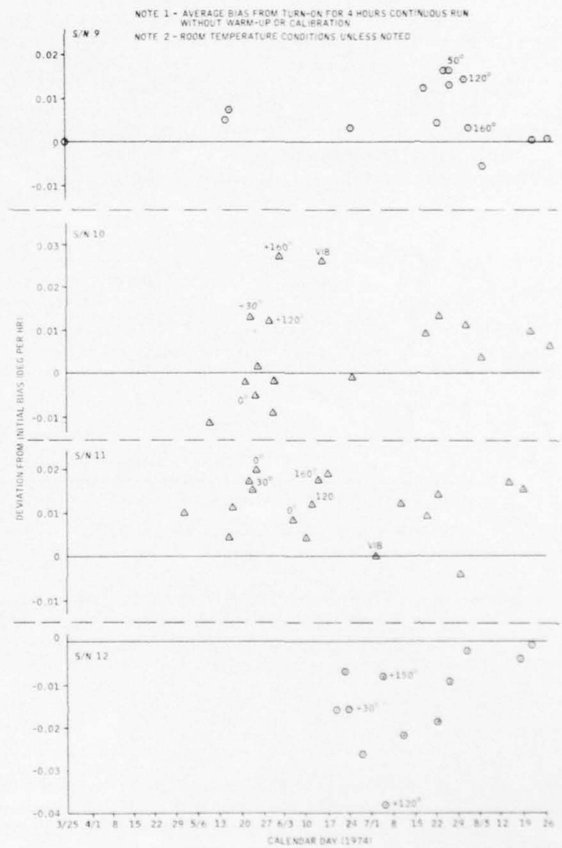


Figure 14. GG1300 S/N 9-12 Bias Stability

CALIBRATION AND STATIC LAB TESTING

Calibration of the system sensor components allows precise compensation within the flight computer software for various sensor anomolies. The gyros and accelerometers are calibrated to determine bias, scale factor, and misalignment errors. In addition, the gyro temperature-dependent bias coefficients and the accelerometer temperature-dependent scale factor coefficients are determined. Once the sensor errors are known and are properly compensated for in the system software, testing of the fully integrated system can begin in a laboratory environment. The laboratory tests are comprised of sample alignments at all points of the compass and stationary navigation runs following each alignment.

The RMS heading error profiles for five consecutive LINS laboratory alignment sequences are shown in Figure 15 for north and east ISA orientations. The predominant disturbing influence affecting the alignment convergence in these results is gyro random walk. The system under test had 0.0035 deg/h$^{1/2}$ in the Y-axis gyro and 0.008 deg/h$^{1/2}$ in the X-axis gyro, which is clearly manifested by a more rapid alignment convergence when the Y axis is pointing east. These results are representative of the normally expected range of alignment convergence times for the 1975 LINS flight test system. For today's GG1300 laser gyro technology, 0.005 deg/h$^{1/2}$ is typical of random walk error (between North and East results in Figure 15). Faster convergence performance will be more typical of future LINS systems with the benefits of improved gyro performance through production learning.

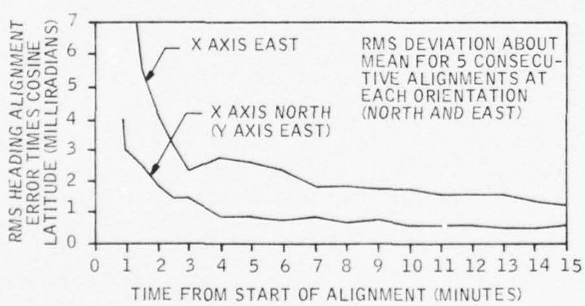


Figure 15. LINS Azimuth Alignment Angle vs. Alignment Time for Five Alignment Sequences with North and East System Headings

VAN TESTING

Van testing of the LINS system (in the three-axis orthogonal gyro mode) was carried out over a one month period, during which eight navigation runs were conducted and performance analyzed. As a preliminary to the van testing, a set of detailed county road maps for the Minneapolis area were used in deriving the latitude and longitude of easily identifiable landmarks (bridges, overpasses, intersections, etc.). Three routes were selected for van testing: the first was almost due north, the second almost due east, and the third was a closed circuit on the Twin City freeway system.

During actual van testing, the LINS latitude and longitude was recorded as each landmark was passed and was compared with the landmark latitude and longitude, giving a series of position errors as a function of elapsed time. Checkpoints were chosen such that an error measurement would be available every five minutes on the average. The duration of a typical van test was approximately 84 minutes (one Schuler period), with the longest run being about 3 hours. A bulls-eye plot of navigation errors at 84 minutes (error at 84 minutes divided by time) is shown for the series of eight van tests in Figure 16. The median radial error of 0.82 nmi/h at 84 minutes for the van runs (see Figure 16) is representative of the CEP at 84 minutes, and also the mean CEP growth rate for the system since oscillatory error terms tend to be at null at one Schuler period.

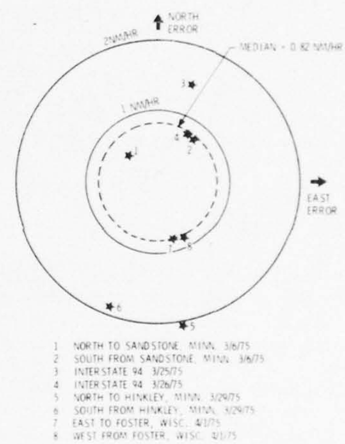


Figure 16. Bulls-Eye Plot of LINS Van Test Navigation Errors at 84 Minutes

HOLLOMAN TEST CONDITIONS

The LINS engineering hardware (3-axis orthogonal gyro mode configuration) was delivered to Holloman Air Force Base on April 14, 1975. Final system calibrations were completed on April 16, 1975. From April 16, 1975 until completion of the Holloman test program on July 14, 1975, no system calibrations were performed. Over 268 operating hours were accumulated on the system during the test period (including 82 aircraft navigation operating hours and 65 aircraft navigation flight hours) with no system failures.

All system tests were performed without temperature controls. For the C-141 flights, approximately 40°F temperature variations were experienced during the tests (high aircraft internal temp-

erature at system turn-on on the ground followed by cool-down to 70°F or lower after the engines were started and aircraft air conditioning systems began operating).

All system test runs were initiated from a cold condition (preceeded by at least 3 hours of system off time). All system runs entered the navigate mode after 20 minutes from turn-on (10 minutes for warm-up and 10 minutes for alignment). An exception was the eighth flight test run where an extended warm-up period (50 minutes) was needed for memory loading procedures.

All system alignments were performed inertially with no a priori knowledge of coarse heading. No external optical alignment devices were used in alignment sequence and the only external input to the system during the test program was barometric altitude provided in the C-141 for altitude channel stabilization.

HOLLOMAN LAB TESTING

As a preliminary to the Holloman C-141 flight tests, a series of both fixed and moving base tests were conducted at Holloman Air Force Base. The tests were grouped into four categories:

- Static - Navigational accuracy is determined for a fixed-base condition.
- Scorsby - Navigational accuracy is determined when the base has a ±3° circular coning motion at 6 rpm.
- Static Heading Sensitivity - The effect of periodic heading changes on navigational accuracy is determined for a fixed-base condition.
- Scorsby Heading Sensitivity - The effect of periodic heading changes on navigational accuracy is determined for Scorsby base motion (described above).

All tests were 6 hours in duration and began after a 10-minute warm-up and 10-minute alignment. A summary of navigational accuracy determined for the series of lab tests is shown in Table 1.

Table 1. Holloman Lab Test Results

Date	Test Type	End Point Error Rate (Radial Error At 6 Hrs. ÷ 6) (nmi/h)
May 1	Static	0.5
May 2	Scorsby	1.35
May 8	Static	0.63
May 8	Static HDG Sensitivity	0.25
May 9	Scorsby HDG Sensitivity	1.37
May 9	Scorsby HDG Sensitivity	0.45

HOLLOMAN FLIGHT TESTS

Flight testing of the LINS system was conducted at Holloman Air Force Base in a C-141 aircraft during the period from May 14 to June 27, 1975. A total of 13 flight tests were carried out at three Air Force facilities: Holloman Air Force Base (Almagordo, New Mexico); Elmendorf Air Force Base (Anchorage, Alaska); and Eielson Air Force Base (Fairbanks, Alaska). Table 2 gives a general description of the 13 flight test profiles.

Navigational errors for the LINS system were established on each flight by periodic comparisons (typically about once every 5 minutes) of the navigator's indicated position and the known position of a checkpoint being traversed. This provided a set of "quick look" results which was subsequently refined using a photograph of each checkpoint as it was traversed. The photograph is necessary because the checkpoints are not traversed exactly. The adjusted checkpoint position errors also provide the data base for deriving LINS velocity error histories for each flight by using a Holloman data smoothing program.

Table 2. LINS Flight Test Profiles

Flight Test	Location	Align Orientation	Flight Path	Flight Time (Hrs)	Nav Time (Hrs)
1	Holloman (N. M.)	N	N-S	2.83	4.17
2	Holloman (N. M.)	N	W-E	6.13	7.67
3	Holloman (N. M.)	N	N-S	2.97	4.17
4	Holloman (N. M.)	N	W-E	6.05	8.00
5	Holloman (N. M.) to Elmendorf (ALAS.)	N	N/W	9.17	10.37
6	Elmendorf (ALAS.)	E	N-S	3.00	4.25
7	Elmendorf (ALAS.)	E	N-S	3.18	4.67
8	Elmendorf (ALAS.)	N	W-E-W-E	7.13	8.00
9	Eielson (ALAS.)	N	W-E	2.93	4.33
10	Eielson (ALAS.)	N	W-E	2.85	3.92
11	Eielson (ALAS.)	N	N-S-N-S	6.98	8.33
12	Eielson (ALAS.) to Holloman (N. M.)	N	S/E	10.23	11.50
13	Holloman N. M.	N	Circling	1.35	3.00
	Summary Data	Total Hours		64.80	82.38

Two methods were used at Honeywell to compute a figure of merit for position error growth rate.* The first method was recommended by NASC (Naval Air Systems Command) and is the same as that used to evaluate the CAINS (Carrier Aircraft INS) system (Reference). The method is described in the following steps:

*Performance figures given in this paper do not constitute the official results of the flight test (to be published subsequently by Holloman) and in some cases are based on "quick-look" data.

1) The radial error is computed at each of the available checkpoints.

2) Error rates are computed at each checkpoint by dividing the radial error by the elapsed time since entering the navigation mode.

3) The error rates occurring at two successive checkpoints, which are separated by less than 0.1 hour, are averaged and considered to be one value halfway between the two time points.

4) Error rates for each flight are ordered from the smallest value to the highest.

5) The 50-percentile error rate for each flight is chosen as that value which is halfway down the ordered set. Interpolation is used as required.

6) The 90-percentile error rate for each flight is chosen as the value which is 90 percent down the ordered set. Interpolation is used as required.

7) The data from flights are then mixed together in groups according to the number of checkpoints in each flight. The groupings are as follows:

Group	Number of Checkpoints in Each Flight
A	2-4
B	5-7
C	8-11
D	12-17
E	18-25
F	26-36
G	37-52
H	53-74
I	75-105

8) Steps (4) and (5) are repeated for each group to yield a 50-percentile and 90-percentile number for the group.

9) An overall 50-percentile and 90-percentile number for the system is computed from the values for the groups as:

$$P_{50} = \frac{1}{\Sigma N(I)} [\Sigma N(I) P_{50}(I)]$$

$$P_{90} = \frac{1}{\Sigma N(I)} [\Sigma N(I) P_{90}(I)]$$

where

P_{50} = overall 50-percentile error growth rate

P_{90} = overall 90-percentile error growth rate

$N(I)$ = number of flight in Ith grouping

$P_{50}(I)$ = 50-percentile value for Ith grouping

$P_{90}(I)$ = 90-percentile value for Ith grouping

The results of the above procedure is shown in Table 3 for the LINS flight test data. Data from only the first twelve flights were used. The thirteenth flight test did not yield valid position reference data for comparison due a procedural problem on the C-141.

The second method of processing the position error data is by using a conventional ensemble statistical approach. In this method, the following steps are followed.

Table 3. Fifty and Ninety Percentile Radial Position Error Rates for Twelve LINS Flight Tests. (CAINS Formula)

Flight	No. of Checkpoints of No.	Position Error Rate 50 Percentile (nmi/h)	90 Percentile (nmi/h)
1	23	0.62	1.08
2	27	0.46	0.93
3	26	0.44	1.04
4	28	0.56	1.13
5	30	0.71	1.05
6	19	1.63	3.06
7	23	1.40	1.70
8	34	0.53	1.21
9	22	0.41	1.05
10	16	0.67	2.41
11	29	0.77	1.30
12	43	0.86	1.62
Group	**Flights In Group**	**50 Percentile (nmi/h)**	**90 Percentile (nmi/h)**
D	10	0.67	2.41
E	1, 6, 7, 9	0.91	1.91
F	2, 3, 4, 5, 8, 11,	0.53	1.13
G	12	0.86	1.62
	Total	0.70	1.54

1) The radial error is computed at each of the available checkpoints.

2) The radial errors occurring at two successive checkpoints, which are separated by less than 0.1 hour, are averaged and considered to be one value halfway between the two time points.

3) At each time point (between 0 and 8 hours), the ensemble of radial errors for all flights is ordered, from the smallest to the highest, from which 50-percentile and 90-percentile values are computed. The time points are separated by 0.1-hour increments. Interpolation between actual checkpoint data is used as required.

4) A least-squares straight line fit to the 50-percentile and 90-percentile radial error ensemble results is carried out. The slope of the best fit straight line can be considered as the radial error growth rate.

The results for the second method are shown in Figure 17. It should be noted that the radial error growth rates compare reasonably well with those given in Table 3.

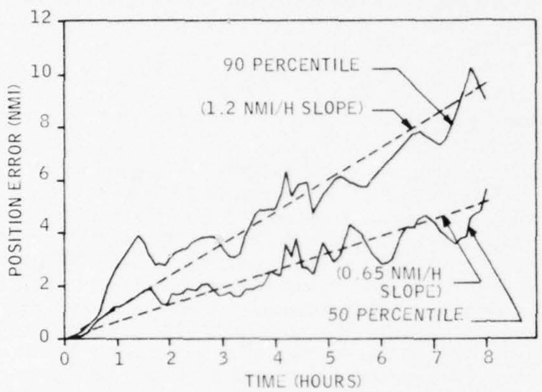


Figure 17. Fifty and Ninety Percentile Flight Test Ensemble Radial Position Errors as a Function of Navigation Times

Velocity errors for inertial navigation systems are generally larger than the average position error rate due to excitation of Schuler oscillations. The velocity errors can be conveniently characterized by an RMS value. An RMS value for each axis can be computed for a given flight from:

$$\sigma_V = \sqrt{\frac{\sum_{i=1}^{N} \delta V_i^2}{N}}$$

where

σ_V = RMS velocity error (north or east)

δV_i = instantaneous velocity error at ith time point in the flight

N = total number of points in the flight

The total RMS value for an ensemble of flights is computed from:

$$\sigma_{V_{TOT}} = \sqrt{\frac{\sum N(I)\sigma_V^2(I)}{\sum N(I)}}$$

where

$\sigma_{V_{TOT}}$ = total RMS velocity error (north or east)

σ_V = RMS velocity error for Ith flight (north or east)

N(I) = number of velocity errors for the Ith flight

It is easy to verify that the above expression yields the same result that would be obtained if the velocity errors for each flight were mixed together without any distinction.

The velocity errors for the LINS flight testing as noted earlier, were derived from smoothed position error information, which was available at 5-minute intervals except during overwater segments. The RMS velocity errors over the first 3 hours of flight using the described procedure are given in Table 4 for flights 1 through 11 individually, and as a total ensemble (due to procedural problems on the C-141, data from flights 12 and 13 was not considered valid for accurate velocity reference determination and was excluded for velocity error analysis).

Table 4. RMS North and East Velocity Errors for Eleven LINS Flight Tests

Flight	No. Of Samples	RMS North Velocity Error (ft/sec)	RMS East Velocity Error (ft/sec)
1	36	3.6	6.2
2	25	3.7	3.2
3	36	1.9	2.8
4	33	7.2	2.9
5	36	3.4	4.2
6	36	11.4	6.4
7	36	3.3	3.5
8	36	5.7	6.3
9	36	5.2	5.4
10	36	8.0	6.1
11	36	4.5	5.6
Total	382	5.9	5.0

A second method of processing the velocity error data is by ensemble processing. This method of processing yields a greater understanding of the time dependency of the velocity errors. At each 5-minute time point (between 0 and 3 hours), an RMS value is computed for each axis using the instantaneous velocity errors in the ensemble of flights. Each flight is used only during periods when checkpoint data was available, and interpolation is not utilized during overwater segments. The time-dependent RMS velocity errors are shown in Figure 18.

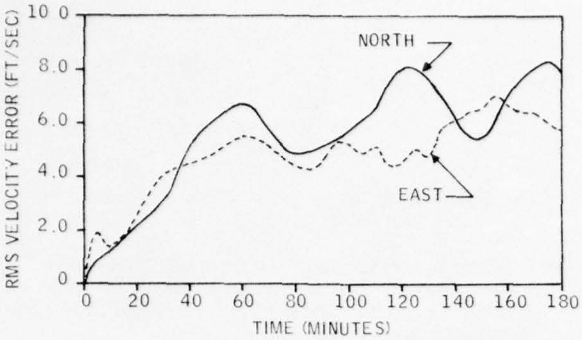


Figure 18. Holloman Flight Test Ensemble RMS Velocity Errors vs. Time

TEST RESULTS ANALYSIS

Analysis of the LINS test results demonstrates that the inertial positioning accuracy achievable with current technology GG1300 laser gyros (Table 3 and Figure 17) is well within the classical 1-2 nmi/h CEP envelop requirement for inertial navigation equipment. The measured inertial velocity accuracy (Table 4 and Figure 18) of 5.5 fps RMS per axis (RMS average for first 3 hours) and 7.5 fps RMS at 3 hours is acceptable for many applications, but will be improved in future LINS design configurations to better satisfy overall military weapons delivery requirements (3 to 5 fps RMS desired). These improvements will be realized in the future through a reduction of errors in three primary areas: laser gyro random walk, laser gyro thermal gradient error (transient bias shifts induced by aircraft internal ambient temperature changes), and sensor-to-sensor alignment uncertainties.

Laser gyro random walk error will improve with learning as gyro producibility is developed for large-scale manufacturing. Reduction of gyro thermal transient sensitivity by a factor of five has already been demonstrated on recent laser gyro design configurations. This is the magnitude of improvement needed, not only for transport-type aircraft application where 40°F temperature transients appear (as in the C-141 at Holloman), but also for fighter aircraft where thermal transients of 100°F can be induced during large altitude change maneuvers. In addition, to reduce the magnitude of thermal gradients induced across the gyros in future LINS configurations, ISA thermal design will concentrate on thermally isolating the sensor/mount assembly from internally-induced system electronics heat, and ensuring symmetrical heat-flow paths between internal and external system environments.

Sensor-to-sensor alignment instabilities in the LINS engineering hardware are caused by two effects: 1) the large single casting in the ISA that serves the dual function of sensor mount and ISA case, and 2) stresses induced in the ISA casting by the gyro/mount interface. The first effect allows ISA large spanwise loads (induced by thermal gradients and mechanical/inertial stresses) to distort the casting and sensor-to-sensor alignments. New LINS design configurations will use an isolated sensor mount/casting that installs into the INS case to eliminate this error mechanism. The second effect is created by the four gyro case corner tie-downs (see Figure 2) used to inhibit gyro case vibration. The gyro input-axis alignment surface is a polished flat at the base of the center post of the instrument (see Figure 2). The principal gyro mechanical interface with the ISA is a bolt through the gyro center post that interfaces the gyro center post flat with a mating reference flat on the ISA sensor block. Anchoring the four gyro case corners after the center post is torqued down introduces distortion stresses into the ISA casting. In future LINS configurations, the sensor case interface with the sensor mount casting will be achieved using flexible tiedowns that have sufficient damping to eliminate case vibrations without introducing spurrious stresses into the sensor casting.

CONCLUSIONS

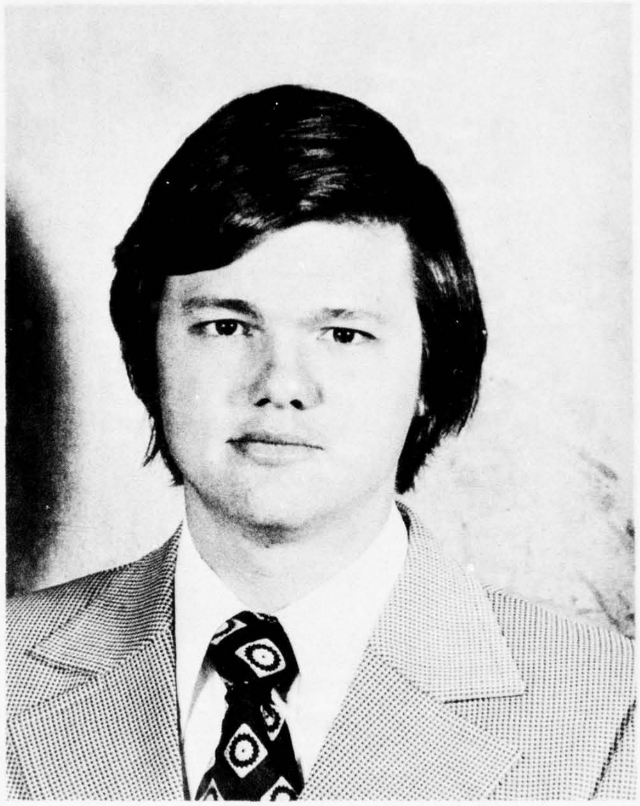
Laboratory, road, and flight tests conducted with LINS engineering hardware in 1975 have demonstrated the ability of today's laser gyro strapdown technology to meet basic military inertial navigation performance requirements. Producibility and reliability development is now required to realize the projected cost advantages of strapdown laser gyro technology in military production applications. Honeywell is currently under contract with the Naval Air Systems Command (NASC) for laser gyro producibility/reliability development and fabrication of a single package laser gyro navigator advanced development unit (sensors, computer, memory, power supply in a single chassis) for reliability and performance evaluation over full military environments in transport, patrol, fighter, or rotary-wing aircraft, for both land based and stringent sea based (carrer alignment, catapault launch, and landing arrest) operation. The advanced development hardware program will provide baseline system reliability and maintainability data for subsequent production development programs to ensure that the maximum cost-of-ownership potential is achieved with laser gyro/strapdown technology in future military applications.

REFERENCE

Guidelines for Evaluation of the Carrier Aircraft Inertial Navigation System (CAINS), Dynamic Research Corporation, September 10, 1972.

BRIEFING TITLE

CAINS IMU TECHNOLOGY IN THE 1980s



ALBERT J. TASCHNER

Albert J. Taschner received his BS Electronics Engineering Degree from the University of Pittsburgh, Pennsylvania in 1969 and has also attended San Diego State University, Graduate School. He has been with the Naval Air Rework Facility, North Island, San Diego, California since 1971. His areas of interest have all dealt with the subjects of Guidance, Control, and Navigation. Since 1973, he has concentrated on the subject of Carrier Aircraft Inertial Navigation Systems. Mr Taschner is currently head of Inertial Navigation Systems Section in the Avionics and Components Engineering Division at the Naval Air Rework Facility, North Island.

CAINS IMU

TECHNOLOGY

IN THE 1980'S

INTRODUCTION

LADIES AND GENTLEMEN, MY NAME IS ALBERT TASCHNER AND I WORK FOR THE INERTIAL NAVIGATION AND INSTRUMENTS BRANCH AT THE NAVAL AIR REWORK FACILITY, NORTH ISLAND, SAN DIEGO, CALIFORNIA. MY SUBJECT THIS MORNING WILL BE CAINS IMU TECHNOLOGY IN THE 1980'S.

FIRST, I WANT TO GIVE A BRIEF OVERVIEW OF THE AN/ASN-92(V) CAINS. AFTER THAT, I WILL DISCUSS THE AN/ASN-130, CAINS-1A, DEVELOPMENT EFFORT FOR THE F-18 AIRCRAFT, AND FINALLY, I WILL TALK ABOUT THE PLANS FOR A CAINS-II STRAPDOWN INERTIAL SYSTEM.

CAINS APPLICATIONS

CARRIER/AIRCRAFT APPLICATIONS

AIRCRAFT	*CARRIERS*
F-14	SARATOGA
S-3A	ENTERPRISE
E-2C	KENNEDY
A-6E	AMERICA
RF-4B	CONSTELLATION
	NIMITZ

CAINS APPLICATIONS

THE AN/ASN-92(V) CARRIER AIRCRAFT INERTIAL NAVIGATION SYSTEM (CAINS) HAD ITS BEGINNING IN THE LATE 1960'S WHEN THE DEVELOPMENT WORK WAS INITIATED TO PROVIDE A COMMON INERTIAL NAVIGATION SYSTEM FOR THE F-14, S-3A, AND E-2C AIRCRAFT. THE COMPETITIVE CONTRACT AWARD FOR CAINS WAS MADE IN MAY 1969. THE FIRST FLIGHT WAS MADE IN MARCH 1971, AND THE SYSTEM MET ITS ACCURACY/ALIGNMENT GOALS IN MARCH 1973. FIRST FLEET DEPLOYMENT WAS MADE IN AUGUST 1973 ON THE USS ENTERPRISE CONCLUDING THE INTENSIVE SEVEN YEAR PERIOD OF DEVELOPMENT.

THE PRESENT CAINS AIRCRAFT APPLICATIONS HAVE SINCE BEEN EXTENDED TO INCLUDE BOTH THE A-6E AND RF-4B AIRCRAFT. THE FULL 5-BOX CAINS SYSTEM CONSISTS OF:

1. INERTIAL MEASURING UNIT
2. POWER SUPPLY UNIT
3. AIR NAVIGATION COMPUTER UNIT
4. CONTROL INDICATOR UNIT
5. CONVERTER AMPLIFIER UNIT

CAINS CONFIGURATIONS

	E-2C	RF-4B	S-3A	F-14A	A-6E
INERTIAL MEASURING UNIT	X	X	X	X	X
POWER SUPPLY UNIT	X	X	X	X	X
AIR NAVIGATION COMPUTER UNIT	X	X	X		
CONTROL INDICATOR UNIT	X	X			
CONVERTER AMPLIFIER UNIT	X	X			

CAINS CONFIGURATIONS

THIS CHART SHOWS THE VARIOUS CAINS CONFIGURATIONS AND THEIR APPLICATION TO EACH OF THE FIVE AIRCRAFT USING CAINS. THE CONVERTER AMPLIFIER UNIT FOR THE E-2C AND THE RF-4B ARE NOT INTERCHANGEABLE DUE TO THE UNIQUE AIRCRAFT INTERFACE REQUIREMENTS OF EACH AIRCRAFT.

CAINS CAPABILITY

- RAPID REACTION ON-BOARD CARRIER
- HIGH ACCURACY NAVIGATION
- READILY ADAPTED TO VARIETY OF WEAPON SYSTEMS

CAINS CAPABILITY

SATISFYING ALL THE REQUIREMENTS OF DIFFERENT AIRCRAFT WITH DIFFERENT MISSIONS REQUIRED CAINS TO HAVE A CAPABILITY NOT NORMALLY FOUND IN ANY ONE INERTIAL NAVIGATION SYSTEM. FOR AN "AT SEA" CAPABILITY, THE SYSTEM WAS REQUIRED TO HAVE RAPID REACTION CAPABILITY. THIS RAPID REACTION REQUIRED THE AIRCRAFT TO BE READY FOR CATAPULT WITHIN MINUTES FROM SYSTEM TURN-ON. A UNIQUE ALIGNMENT FILTER, SMAL (SINGLE MODE ALIGNMENT) WAS DEVELOPED BY NAVAL AVIONICS FACILITY, INDIANAPOLIS (NAFI) TO MEET CAINS SPECIFICATIONS. THE CAINS SYSTEM USES DIGITAL DATA LINK FOR NORMAL ALIGNMENT WITH THE SHIP'S INERTIAL NAVIGATION SYSTEM (SINS). BACK-UP ALIGNMENT IS ACCOMPLISHED BY USE OF AN UMBILICAL CABLE OR VIA MANUAL INPUTS TO THE CONTROL INDICATOR.

DURING ALIGNMENT THE AIRCRAFT MAY AT ANYTIME TAXI, SUSPENDING THE ALIGNMENT UNTIL THE AIRCRAFT'S PARKING BRAKE HAS BEEN RESET, WITH THE ALIGNMENT THEN CONTINUING.

WITH THE CAINS USE IN ELECTRONIC WARFARE AIRCRAFT, AND RECONNAISSANCE AIRCRAFT, A NEED FOR A HIGH ACCURACY NAVIGATION SYSTEM EXISTED. THE CAINS COMPUTER AUTOMATICALLY SELECTS THE MOST ACCURATE OPERATING MODE BETWEEN INERTIAL-DOPPLER, INERTIAL, DOPPLER, OR ATTITUDE HEADING REFERENCE MODES. THE REQUIREMENT OF THE ATTACK COMMUNITY DICTATED A HEADING ACCURACY, AND THE FIGHTER COMMUNITY REQUIRED VELOCITY ACCURACIES. AS A RESULT THE CAINS WAS DESIGNED TO BE READILY ADAPTABLE TO A VARIETY OF WEAPON SYSTEMS WHERE THE BASIC BLACK BOXES ARE COMMON AND ONLY THE AIRCRAFT AVIONICS INTERFACE BOX IS UNIQUE TO EACH APPLICATION.

AN/ASN-130

CAINS-1A

DESIGN GOALS

AN/ASN-130 CAINS-1A DESIGN GOALS

DUE TO THE SUCCESSFUL UTILIZATION OF CAINS IN FIVE NAVY AIRCRAFT. NAVAL AIR SYSTEMS COMMAND (NAVAIR) IS PLANNING TO CONTINUE DEVELOPMENT OF A NEW TECHNOLOGY CAINS-1A SYSTEM, WHICH HAS BEEN DESIGNATED AS THE AN/ASN-130.

CAINS-1A TWO-BOX SYSTEM

INERTIAL MEASURING UNIT (IMU)

- LATEST TECHNOLOGY INERTIAL PLATFORM
- BACKFIT COMPATIBLE WITH CAINS-1

SIGNAL DATA CONVERTER UNIT (SDCU)

- CARRIER ALIGNMENT AND INERTIAL COMPUTATIONS
- 1553 MUXBUS TERMINAL
- I/O INTERFACE FUNCTIONS
- AC/DC POWER SUPPLY

CAINS-1A TWO-BOX SYSTEM

THE CAINS-1A WILL BE A TWO-BOX SYSTEM IN ITS APPLICATION FOR THE F-18 REQUIREMENT. THE INERTIAL MEASURING UNIT (IMU) WILL CONTAIN THE LATEST TECHNOLOGY IN INERTIAL PLATFORMS, USING STATE-OF-THE-ART DRY INSTRUMENTS AND LSI TECHNOLOGY. IT WILL ALSO BE BACKFIT COMPATIBLE WITH THE CAINS IMU, AND IS TO BE PROCURED AS A PREFERRED SPARE FOR FUTURE BUYS OF THE CN-1263/ASN-92 IMU.

THE SIGNAL DATA CONVERTER CV-3359(XN)/ASN-130 WILL PROVIDE ALL THE SYSTEM ALIGNMENT AND INERTIAL NAVIGATION COMPUTATIONS AS WELL AS THE SYSTEM/AIRCRAFT AVIONICS INPUT AND OUTPUT INTERFACE FUNCTIONS. IT WILL CONTAIN MIL-STD-1553 MULTIPLEX BUSS TERMINALS AS WELL AS ALL AC AND DC POWER SUPPLIES NECESSARY IN THE SYSTEM. EMERGENCY POWER FOR TRANSIENT INTERRUPTS WILL BE OBTAINED FROM THE AIRCRAFT BATTERY TO AVOID LOSS OF NAVIGATION INFORMATION.

THE REASONS FOR DEVELOPING A TWO-BOX SYSTEM OVER A ONE-BOX SYSTEM ARE:

1. THE COST OF REPLACEMENT SPARES FOR A ONE-BOX SYSTEM WOULD BE HIGHER BECAUSE OF THE RECALIBRATION REQUIREMENTS OF THE INERTIAL INSTRUMENTS.
2. INERTIAL INSTRUMENTS ARE EASILY DAMAGED BY HANDLING. WITH THE TWO-BOX SYSTEM, LESS REMOVALS OF THE IMU WILL RESULT IN LESS FAILURES.
3. DUAL BOX CONFIGURATION ALLOWS THE IMU TO BE DESIGNED TO BACKFIT AS A PREFERRED SPARE FOR F-14, S-3A, E-2C, A-6E AND RF-4B APPLICATIONS, AND ALLOWS IT TO BE COMPATIBLE WITH CURRENT IMU TEST EQUIPMENT.
4. THE TWO-BOX CONFIGURATION ALLOWS FOR FUTURE REPLACEMENT OF THE IMU WITH ADVANCED TECHNOLOGY INERTIAL MEASUREMENT DEVICES.

CAINS-1A IMU CHARACTERISTICS

- USE EXISTING ASN-92 LOGISTICS
- DECREASE WEIGHT AND SIZE
- MAINTAIN ASN-92 ACCURACY AND INCREASE RELIABILITY

CAINS-1A IMU CHARACTERISTICS

THE MAJOR GOALS IN DEVELOPING THE CN-1476(XN)/ASN-130 CAINS-1A IMU WERE TO MAINTAIN COMPATIBILITY WITH THE EXISTING CN-1263/ASN-92 CAINS IMU GROUND SUPPORT EQUIPMENT INTERFACE AND AIRCRAFT INTERFACE, AND AT THE SAME TIME DECREASE WEIGHT AND SIZE WITH AN INCREASE IN RELIABILITY. THE ASN-92 ACCURACIES AND RAPID ALIGN REQUIREMENTS ARE ALSO TO BE MAINTAINED IN THE ASN-130, WHERE POSSIBLE. WITH AN IMU RELIABILITY GOAL OF 2000 HRS MEAN TIME BETWEEN FAILURE (MTBF) IN THE FIELD, IT IS CONCEIVABLE THAT THE REQUIREMENT FOR TEST EQUIPMENT ABOARD AIRCRAFT CARRIERS MAY BE ELIMINATED. NAVAIR IS ALSO CONSIDERING THE POSSIBILITY OF A RELIABILITY IMPROVEMENT WARRANTY (RIW) PROCUREMENT FOR THE FIRST 5 TO 8 YEARS OF THE AN/ASN-130.

CAINS-IA GYRO

- NONFLOATED, TWO DEGREE OF FREEDOM
- RUGGED FLEXURE JOINT
- LOW COST BALL BEARING DESIGN
- REDUCED TEMPERATURE GRADIENT SENSITIVITY

CAINS-1A GYRO

THE CAINS-1A GYRO WILL BE A NONFLOATED, TWO-DEGREE OF FREEDOM GYRO. THE GYRO WILL CONSIST OF AN INERTIAL ROTOR, A MOTOR, FLEXURE SUSPENSION CONNECTING THE TWO, A COMPENSATION WEIGHT, A TWO-AXIS PICKOFF, A TWO-AXIS TORQUER AND TEMPERATURE CONTROL SENSORS. ITS UNIQUE FEATURE IS A SPECIAL ROTATING FLEXURE SUSPENSION ON ONE END OF A SHAFT, SUPPORTING AND PIVOTING THE WHEEL AND ELIMINATING ALL SPHERICAL FRICTIONAL RESTRAINTS. THE OTHER SHAFT END IS DRIVEN BY A SYNCHRONOUS-HYSTERESIS MOTOR.

IMPROVED BALL BEARINGS WILL BE USED IN THE SPIN MOTOR SHAFT. REDUCED TEMPERATURE SENSITIVITY IS ACHIEVED BY INCORPORATION OF A MORE STABLE LAMINATED PICKOFF, A ONE PIECE FLYWHEEL, AND ELIMINATION OF FLUID CONVENTION CURRENTS AND MINIMAL THERMAL GRADIENTS. THE DRY INSTRUMENT DESIGN OFFERS EXCELLENT WARM-UP STABILIZATION CHARACTERISTICS THAT HAVE SMOOTH AND REPEATABLE RESPONSES.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CAINS AND CAINS-1A GYROS

THIS VIEWGRAPH SHOWS THE CAINS G-300G2 GYROSCOPE AND THE NEW CAINS-1A GYROSCOPE.

CAINS-IA ACCELEROMETER

- DRY FLEXURE SUPPORTED DESIGN
- CAPACITIVE/OPTICAL PICKOFF
- ADVANCED MAGNET MATERIALS

CAINS AND CAINS-1A GYROS

THIS VIEWGRAPH SHOWS THE CAINS G-300G2 GYROSCOPE AND THE NEW CAINS-1A GYROSCOPE.

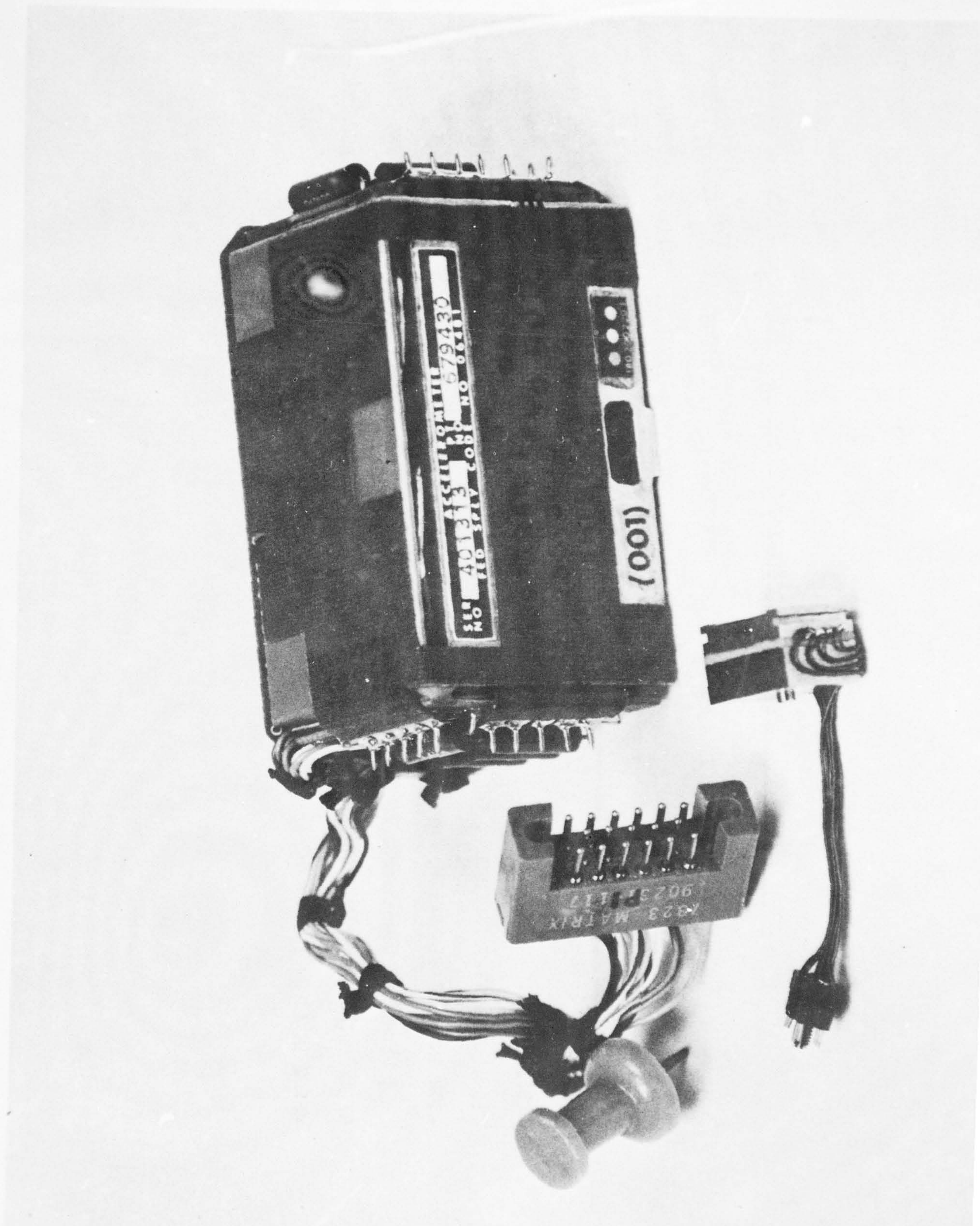
CAINS-IA ACCELEROMETER

- DRY FLEXURE SUPPORTED DESIGN
- CAPACITIVE/OPTICAL PICKOFF
- ADVANCED MAGNET MATERIALS

CAINS-1A ACCELEROMETER

THE CAINS-1A ACCELEROMETER IS A SUBMINIATURE, SINGLE-AXIS, PENDULOUS, LINEAR ACCELEROMETER AND OFFERS EXCELLENT PERFORMANCE COMBINED WITH A MINIMUM OF COMPLEXITY FOR EQUALLY EXCELLENT INHERENT PRODUCIBILITY. THE ONE-PIECE FLEXURE HINGE AND PENDULOUS ASSEMBLY OFFERS IMPROVED MECHANICAL STABILITY AS WELL AS REDUCED COMPLEXITY. CAPACITIVE OR OPTICAL PICKOFFS WILL BE UTILIZED WITH INTEGRAL PREAMPLIFIERS AND GREATLY INCREASED VOLTAGE OUTPUTS COMPARED TO CONVENTIONAL INDUCTIVE PICKOFFS. THE PERMANENT MAGNET TORQUERS WILL CONTAIN ADVANCED MAGNET MATERIALS WITH INHERENT LINEARITY.

ONLY THREE SUBASSEMBLIES WILL BE INTEGRATED AT FINAL ACCELEROMETER ASSEMBLY RESULTING IN A WELL CONTROLLED, LOW COST AND HIGH YIELD INSTRUMENT. LIKE THE CAINS-1A GYROSCOPE, THE ACCELEROMETER IS A DRY INSTRUMENT DESIGN WHICH OFFERS EXCELLENT RAPID REACTION CAPABILITY.



CAINS AND CAINS-1A ACCELEROMETER

THIS VIEWGRAPH SHOWS THE CAINS A-200D ACCELEROMETER AND THE NEW CAINS-1A ACCELEROMETER.

ADVANTAGES OF CAINS-1A APPROACH

- MINIMUM SIZE AND WEIGHT
- FUTURE REQUIREMENTS COMPATIBLE
- BACKFIT COMPATIBILITY
- INERTIAL PLATFORM SUPPORT COMMONALITY
- OPERATIONAL COST EFFECTIVENESS

ADVANTAGES OF CAINS-1A APPROACH

THE ADVANTAGES THAT NAVAIR EXPECTS TO REALIZE IN THE CAINS-1A ARE AN IMU WITH DECREASED SIZE AND WEIGHT, AN INCREASE IN MEAN TIME BETWEEN REMOVALS (MTBR) AND INCREASE IN MEAN TIME BETWEEN FAILURE (MTBF) AND MAINTAIN ASN-92 SPEC REQUIREMENTS. THE CRITICAL ENVIRONMENT OF THE F-14 WHERE SHOCK LEVELS OF 17 G'S FOR 35 MILLISECONDS EXIST HAVE RESULTED IN A REQUIREMENT THAT THE CAINS-1A BE CAPABLE OF WITHSTANDING AT LEAST 20 G'S FOR 40 MILLISECONDS. THE LATEST TECHNOLOGY AVAILABLE FOR INERTIAL INSTRUMENTS WILL BE UTILIZED IN THE CAINS-1A. THE ASN-130 IMU WILL BE 100 PERCENT INTERCHANGEABLE WITH THE ASN-92 IMU. IT IS TO BE PROCURED AS A PREFERRED SPARE FOR ANY FUTURE AIRCRAFT PROCUREMENTS. THIS INTERCHANGEABILITY WILL REDUCE THE PROLIFERATION OF INERTIAL SYSTEMS THAT EXISTED IN THE PAST WITH EACH NEW AIRCRAFT INTRODUCTION INTO THE FLEET. IN THE PAST EACH AIRCRAFT HAD ITS OWN UNIQUE INERTIAL SYSTEM ALONG WITH ITS ASSOCIATED SUPPORT EQUIPMENT RESULTING IN A LARGE DUPLICATION OF SUPPORT REQUIREMENTS FOR BOTH THE AVIONICS AND THE SUPPORT EQUIPMENT. A COMMON POOL OF SPARE INERTIAL MEASURING UNITS USED ON FIVE OR SIX AIRCRAFT WITHOUT MODIFICATION OR CHANGES INCREASES THE AVAILABILITY OF READY-FOR-ISSUE (RFI) UNITS, THEREBY REDUCING AIRCRAFT DOWN TIME.

THE OPERATIONAL COST BENEFITS THAT WILL BE REALIZED ARE BUILT IN TEST CAPABILITY ALLOWING FOR QUICK IDENTIFICATION OF FAULTY WEAPON REPLACEABLE ASSEMBLIES. A SUBSTANTIAL INCREASE IN MEAN TIME BETWEEN FAILURE OF THE INERTIAL MEASURING UNIT WILL REDUCE OVERALL LOGISTIC SUPPORT REQUIREMENTS. IT IS ALSO POSSIBLE TO IMPROVE THE RELIABILITY SIGNIFICANTLY ENOUGH TO ELIMINATE ALL SHIPBOARD TEST REQUIREMENTS. ALSO WITH A COMMON IMU FOR DIFFERENT AIRCRAFT, REDUCTION IN THE COST OF THE IMU IS A BENEFIT OF THE LARGE PRODUCTION ORDERS. IT IS ESTIMATED THAT OVER $200 MILLION IN COST AVOIDANCE HAS BEEN REALIZED IN THE CAINS APPLICATION ALONE WITH MORE SAVINGS TO BE REALIZED IN THE CAINS-1A PROCUREMENT.

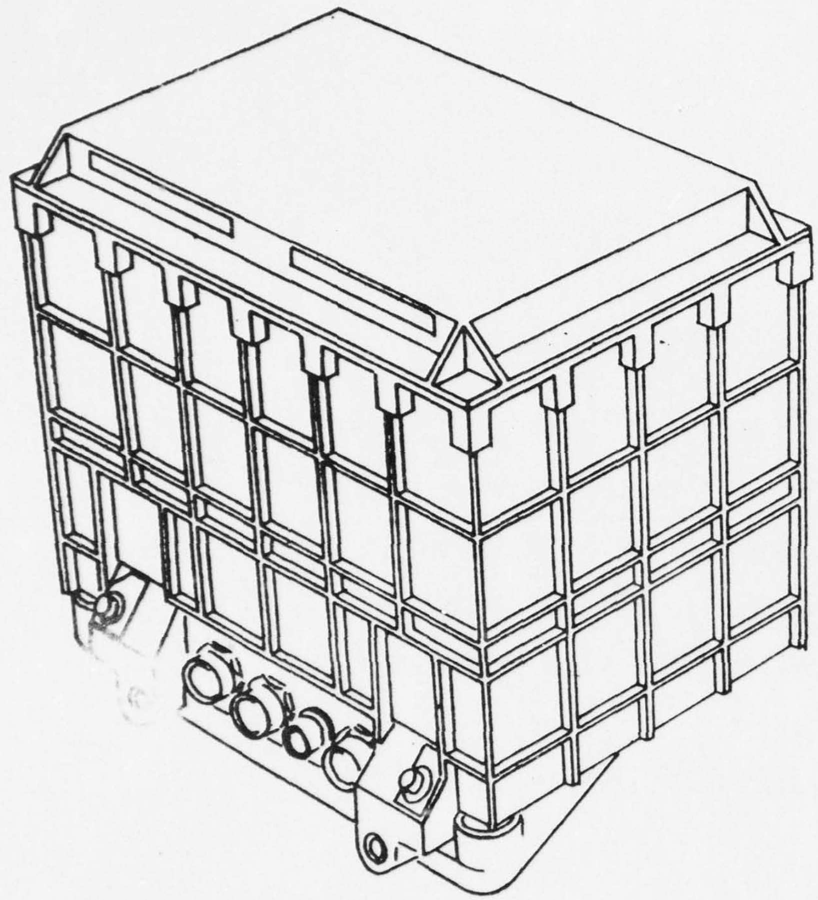
CAINS VS CAINS-1A COMPARISON

CAINS			CAINS-1A		
	VOL. (CU. FT.)	WT. (LB.)		VOL. (CU. FT.)	WT. (LB.)
IMU	.93	37.5	IMU	.28	14.8
ANCU PSU CAU	1.54	80.6	SDCU	.30	13.7
TOTAL	2.47	118.1	TOTAL	.58	28.5

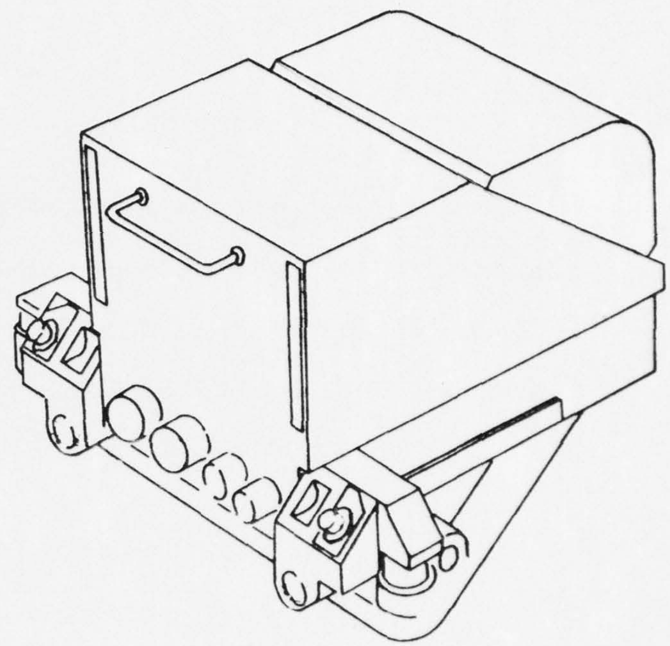
CAINS-1 VS CAINS-1A COMPARISON

THIS CHART COMPARES THE PHYSICAL CHARACTERISTICS OF THE CAINS AND THE CAINS-1A. THE VOLUME AND WEIGHT OF THE CAINS-1A SYSTEM IS EXPECTED TO BE LESS THAN 25 PERCENT OF THE CURRENT CAINS CONFIGURATION. THE CAINS-1A IMU ITSELF WILL BE NO GREATER THAN (H x W x D) 7.5 x 8.0 x 6.0 INCHES COMPARED TO THE CAINS IMU DIMENSION OF 9.7 x 13.6 x 12.2 INCHES, WITH OVER A 50 PERCENT REDUCTION IN WEIGHT.

CAINS-1A INERTIAL MEASURING UNIT BACKFIT COMPATIBILITY



CAINS



CAINS-1A

CAINS-1A INERTIAL MEASURING UNIT

BACKFIT COMPATIBILITY

THE CAINS-1A IMU WILL BE CAPABLE OF MECHANICALLY INTERFACING WITH THE EXISTING CAINS MT-4100/ASN-92 MOUNT. THIS WILL BE ACCOMPLISHED WITH AN ADAPTER MOUNT WHICH MATES TO THE MT-4100 MOUNT. THE CN-1476(XN)/ASN-130 IS THEN CONNECTED TO THE ADAPTER MOUNT. ELECTRICAL CONNECTIONS TO THE AIRCRAFT INTERFACE WILL BE PIN-TO-PIN INTERCHANGEABLE WITH THE CAINS IMU EQUIVALENT REQUIREMENTS. PASSIVE CONNECTOR ADAPTERS SIMILAR TO THE CONNECTOR SAVERS CURRENTLY BEING UTILIZED ON THE ASN-92 IMU WILL BE REQUIRED FOR INTERFACING WITH THE AIRCRAFT CONNECTORS.

THE AIRCRAFT COOLING AIR PLENUMS WILL BE MATED TO THE ASN-130 IMU BY MEANS OF AN ADAPTER PLENUM IF IT IS REQUIRED. AN IMU THAT WOULD NOT REQUIRE AIRCRAFT COOLING AIR IS A POSSIBILITY THAT MAY BE REALIZED IN THIS PROGRAM IN ORDER TO ELIMINATE THE ADAPTER PROBLEM AS WELL AS THE PROBLEM OF SUPPLYING COOLING AIR TO THE AIRCRAFT DURING SYSTEM CHECKOUT.

CAINS-1A ADAPTABILITY TO ASN-92 SUPPORT SYSTEM

- **GSE** — ASN-92A SRA TEST EQUIPMENT ADAPTATION
- **SPARES** — PROCURE AND PROVISION CAINS-1A IMU'S
- **TRAINING** — PIN-FOR-PIN INTERCHANGEABILITY AND FUNCTIONAL COMMONALITY
- **DATA** — FUNCTIONAL COMMONALITY REDUCES COST OF NEW DATA

CAINS-1A ADAPTABILITY TO ASN-92

SUPPORT SYSTEM

THE EXISTING ASN-92 GROUND SUPPORT EQUIPMENT (VAST, IPTS, AND ATS) WILL BE UTILIZED TO SUPPORT THE ASN-130 IMU AND SIGNAL DATA CONVERTER UNIT. THE IMU AND SDCU MODULES WILL BE SUPPORTED WITH THE USE OF VAST (VERSITILE AVIONICS SHOP TESTER). ADAPTION TO THE VAST WILL REQUIRE NEW SOFTWARE TEST PROGRAMS AND INTERCONNECTION DEVICES FOR INTERFACING WITH THE VAST HARDWARE.

SPARES PROCUREMENT FOR THE CAINS-1A IMU'S WILL BE MADE TO SUPPORT BOTH THE EXISTING AIRCRAFT USERS (F-14, S-3A, E-2C, A-6E, AND RF-4B) AND THE FUTURE AIRCRAFT USERS (F-18).

TRAINING WILL BE SIMPLIFIED AND LOWER IN COST BECAUSE OF THE PIN-FOR-PIN FUNCTIONAL INTERCHANGEABILITY WITH THE ASN-92. THE OVERALL COST OF PREPARING NEW DATA FOR THE CAINS-1A WILL ALSO BE LOWER BECAUSE OF THE FUNCTIONAL COMMONALITY.

THE PIN-FOR-PIN INTERCHANGEABILITY AND FUNCTIONAL COMMONALITY ALSO REDUCES THE DEPOT TEST EQUIPMENT REQUIREMENT WITH THE CAPABILITY TO USE EXISTING ASN-92 TEST EQUIPMENT ALREADY AT THE DEPOT.

CAINS-II

RING LASER GYRO

NUCLEAR MAGNETIC RESONANCE GYRO

TUNED ROTOR GYRO

CAINS-II

NAVAIR PLANS TO FOLLOW UP THE CAINS-1A WITH CAINS-II, WHICH WILL BE A STRAPDOWN INERTIAL NAVIGATION SYSTEM. THE CAINS-II SYSTEM IS PLANNED FOR AIRCRAFT REQUIREMENTS IN THE LATE 1980'S. THE INERTIAL INSTRUMENTS THAT ARE UNDER DEVELOPMENT FOR CAINS-II INCLUDE RING LASER GYROS (RLG), NUCLEAR MAGNETIC RESONANCE GYROS (NMR) AND TUNED ROTOR GYROS.

RING LASER GYRO FEATURES

- HIGH ENVIRONMENTAL CAPABILITY
- WIDE DYNAMIC RANGE
- LOW TOTAL COST OF OWNERSHIP
- IDEAL ANGULAR RATE SENSOR FOR STRAPDOWN SYSTEM

RING LASER GYRO FEATURES

SOME FEATURES OF THE RING LASER GYRO IN ITS APPLICATION TO STRAPDOWN INERTIAL SYSTEMS FOR CAINS-II ARE:

1. HIGH G CAPABILITIES ARE POSSIBLE BECAUSE OF GOOD MECHANICAL DESIGN IN A SOLID STATE DEVICE.

2. WIDE DYNAMIC RANGE IS POSSIBLE IN SENSING OF HIGH ANGULAR RATES AS HIGH AS 400 DEG/SEC.

3. WITH MINIMAL MOVING PARTS AND SIMPLICITY OF DESIGN, IT SHOULD BE POSSIBLE TO MASS PRODUCE RLG'S AT A COST LOWER THAN THEIR CONVENTIONAL COUNTERPARTS.

4. IDEAL ANGULAR RATE SENSING IS PROVIDED WITH A HIGH RESOLUTION DIGITAL OUTPUT FREQUENCY PROPORTIONAL TO THE INPUT RATE.

THE MAJORITY OF DEVELOPMENT IN STRAPDOWN INERTIAL SYSTEMS HAS BEEN WITH RING LASER GYROS AND BECAUSE OF THIS THEY APPEAR TO BE THE PRIME CANDIDATE FOR CAINS-II.

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DATA EXCHANGE FOR INERTIAL SYSTEMS (9TH), CONFERENCE PROCEEDING--ETC(U)
SEP 76 E T BODEM

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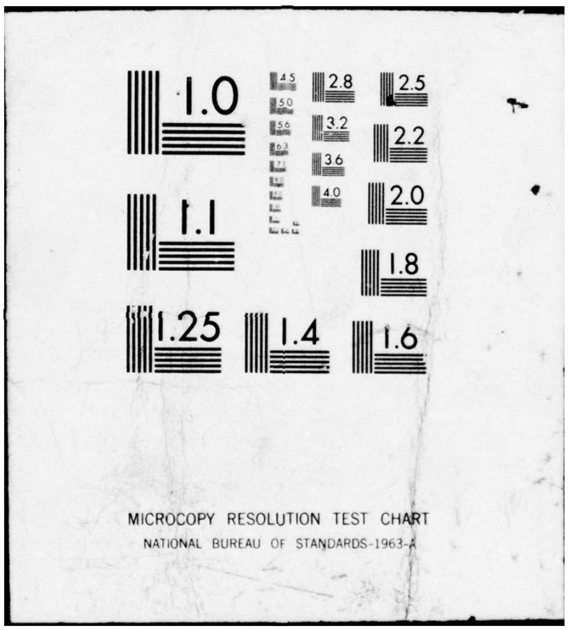
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

NMR GYRO FEATURES

- LOW COST
- HIGH ACCURACY
- HI-G CAPABILITY
- NO MOVING PARTS
- NOT CRITICALLY DEPENDENT ON PHYSICAL DIMENSIONS

NMR GYRO FEATURES

THE NUCLEAR MAGNETIC RESONANCE (NMR) GYRO FEATURES THAT MAKE IT DESIRABLE FOR STRAPDOWN INERTIAL SYSTEMS ARE:

1. BY UTILIZING THE INHERENT ANGULAR MOMENTUM AND MAGNETIC MOMENT PROPERTIES OF THE NUCLEI HIGH ACCURACIES ARE POSSIBLE.

2. HI-G CAPABILITIES ARE POSSIBLE BECAUSE THERE ARE NO MOVING PARTS.

3. WITH NO MOVING PARTS AND A SIMPLE MECHANICAL DESIGN THAT IS NOT CRITICALLY DEPENDENT ON PHYSICAL DIMENSIONS, THE NMR GYRO OFFERS LOW PROCUREMENT COST.

THE NMR GYRO TECHNOLOGY IS STILL IN THE DEVELOPMENT PHASE, BUT APPEARS TO BE AN EXCELLENT CONTENDER FOR STRAPDOWN INERTIAL SYSTEMS.

TUNED ROTOR GYRO FEATURES

- SIZE AND WEIGHT
- PRODUCIBILITY
- TWO-DEGREE-OF-FREEDOM

TUNED ROTOR GYRO FEATURES

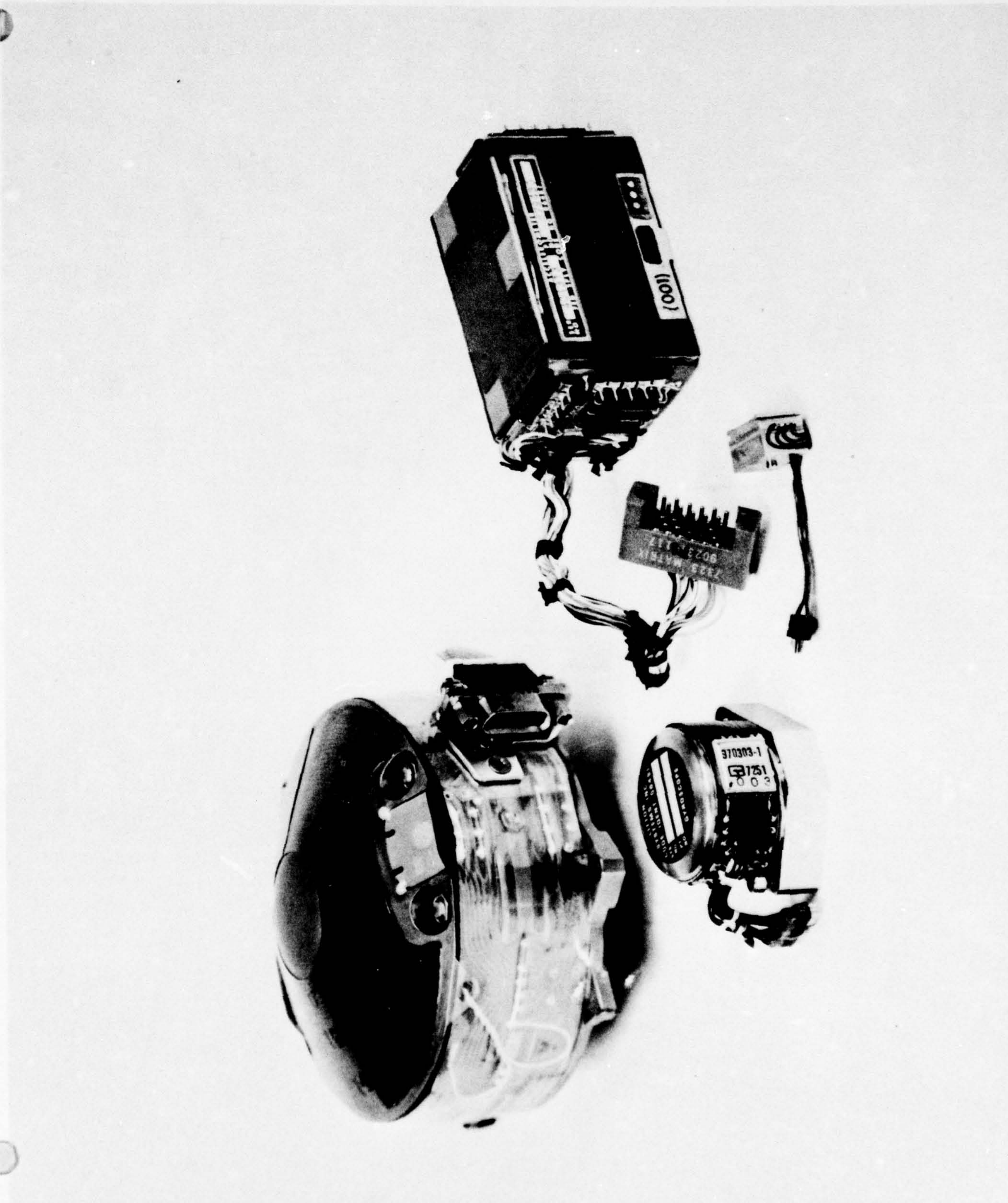
THE TUNED ROTOR GYRO ADVANTAGES FOR STRAPDOWN INERTIAL NAVIGATION SYSTEMS ARE:

1. IT CAN BE PRODUCED IN A SMALLER SIZE AND WITH LESS WEIGHT THAN OTHER STRAPDOWN GYROSCOPES.

2. IT IS PRODUCEABLE AT A SIGNIFICANT YIELD DUE TO ITS SIMILARITY TO CONVENTIONAL GYROSCOPES.

3. THE FLEXURE JOINT PRINCIPLE OF OPERATION OFFERS A TWO-DEGREE OF FREEDOM GYROSCOPE VERSES A ONE-DEGREE OF FREEDOM RLG.

OVER $200 MILLION IN COST AVOIDANCE HAS BEEN REALIZED IN THE CAINS APPLICATION. IT IS ANTICIPATED THAT A SIMILAR COST AVOIDANCE CAN BE ACHIEVED IN THE CAINS-1A PROGRAM. NAVAL AIR SYSTEMS COMMAND ALSO PLANS TO PURSUE THE COMMONALITY APPROACH FOR A STANDARDIZE NAVY STRAPDOWN INERTIAL NAVIGATION SYSTEM FOR AIRCRAFT REQUIREMENTS IN THE LATE 1980'S.



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BRIEFING TITLE

TACTICAL MISSILE GUIDANCE SYSTEM

ARTHUR F. CARBERT

Mr. Carbert received a BS in ME in 1962 and a Master's in 1967 from the University of Minnesota. He joined Honeywell in 1959 and is a Principal Development Engineer at the Aerospace Division in St. Petersburg, Florida. He has been involved in many Guidance and Control System Developments including:

ATHENA-H

BURNER II

SCOUT

SHAG

JAPAN'S ASM

Mr. Carbert presently directed the technical applications of the H478 Inertial Navigation System.

TACTICAL WEAPON GUIDANCE SYSTEM

By

ARTHUR F. CARBERT

Principal Development Engineer

Honeywell Inc.

Aerospace Division

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H-478F/HDC-301 APPLIED TO TACTICAL WEAPONS

1.0 INTRODUCTION

Key features of tactical weapons were identified by the most primitive cultures. Even rocks thrown at wild animals represent key features of tactical weapons, i.e., normally plentiful, small enough to be easily handled and quickly deployed, could be stockpiled at strategic locations, were expendable, and were obviously effective in the right circumstances. Technology has permitted the rock to be replaced by archery, bows and arrows to be replaced by guns, small arms to be replaced by artillery, cannons to be replaced by tanks, wheeled vehicles to be replaced by missiles. Today's tactical weapon technology seems to be evolving into sophisticated combinations of ground, sea, and air vehicles all using some form of tactical weapon support for achievement of military objectives. Despite the complexity of this technology, the basic features of tactical weapons remain virtually unchanged; it is still important to have small, easily stored and quickly deployed, expendable, but effective weapons.

One of the most dramatic technological advances of the last decade has been in electronic packaging. The use of operational amplifiers, integrated circuits, and hybrid electronics has permitted the replacement of discrete components with attendant savings in terms of size, weight, power, and cost. This miniaturization has enhanced the development of tactical weapons and permitted the employment of more sophisticated tactical guidance and control approaches while preserving the small size, weight, and deployment characteristics. Strapdown inertial guidance and control systems are especially suited to tactical weapons because they provide the following advantages:

- Strapdown generally provides for the lowest overall weight, size, and highest reliability.
- Strapdown permits the greatest packaging flexibility.
- Strapdown simplifies the control system mechanization by eliminating the requirement for a separate autopilot rate gyro unit.

Honeywell has developed a small, versatile strapdown system consisting of an H-478 Inertial Sensor Assembly (ISA) and companion HDC-301 computer for use in tactical missiles and related applications. The H-478 ISA was successfully applied to the USAF SHAG (Simplified High Accuracy Guidance) Program which demonstrated helmet sight target acquisition with strapdown inertial guidance for a FALCON missile launched from under the wing of an F101 aircraft.

Currently, the H-478 technology is being applied to a tactical Air-to-Ship Missile (ASM) for JAE (Japan Aviation Electronics), an application similar to the USN Harpoon program. For the ASM, the H-478 has been modified to fit a unique form factor and features the Honeywell HDC-301 computer. ASM functions performed by the H-478/HDC-301 include providing rate and attitude signals to the Autopilot, Guidance, blending of accelerometer and altimeter signals for vertical flight control, initialization of guidance system, mode control and command for vehicle subsystems, mode sequencing for ignition, separation, arming, and destruct. Supporting software modules including special mode controls, coordinate transformation and in-flight alignment have also been developed for the H-478/HDC-301 inertial system.

The current all-up, off-the-shelf INS consists of an H-478B ISA and HDC-301 computer unit. Its features, along with the features of a SHAG ISA and the ASM system, are contrasted in Table 1 with typical requirements for tactical missile guidance equipment. The remainder of this paper examines the H-478F ISA and HDC-301 computer illustrating the features which make the INS or its individual devices suitable for other applications which require performance in the 2 to 10 degree/hour class.

TABLE 1. H-478 AND TACTICAL GUIDANCE REQUIREMENTS

Typical Tactical Weapon Guidance Requirements	H-478 Specifications		
	SHAG Configuration	ASM Configuration	H-478F/HDC-301
Configuration	H-478B ISA only	GG8105 ISA BG8105 Comp	H-478F ISA BG8105 Comp
Small Size (Volume) (Less than 750 in^3)	250 in^3 (4097 cm^3)	415 in^3 (6800 cm^3)	525 in^3 8603 cm^3)
Small Weight (15-25 lb)	5.0 lb 2.3 Kg	15.60 lb 7.1 Kg	18.0 lb 8.2 Kg
Quick Reaction Time (30 sec to 15 min)	<15 min	<10 min	<15 min 1 min w/degraded performance
Low Power Consumption (50-100 watts)	<35 watts	<65 watts	<65 watts

2.0 INERTIAL SENSOR ASSEMBLY

The present configuration of the H-478F ISA is depicted in Figure 1. Three Honeywell GG1111 rate integrating gyros and three Sundstrand Q-Flex accelerometers are mounted in a thermally controlled aluminum block. The block is vibration-isolated from the extruded aluminum chassis. All electronics and power supply mount vertically in the same chassis and are interconnected with a double-sided interconnecting board. End plates and a simple wraparound cover complete the housing. An optical reference is provided on the block for boresighting and view ports are provided through the cover and end plate.

Figure 2 is a simplified functional block diagram for the H-478F. The gyros and accelerometers sense three axis rotations and translation. Analog rebalance signals are conditioned to provide body-sensed analog rate and acceleration inputs. In addition, a signal proportional to the rebalance torque is fed into an integrator which is reset* whenever a precise attitude change occurs. A fixed precision output pulse occurs simultaneously with reset resulting in a train of attitude change pulses which occur at a rate proportional to the sensed rate or acceleration. Nominal device scale factors are as follows:

	Max Pulse Rate	Digital Scale Factor	Analog Scale Factor
Acceleration (X, Y, Z)	12.8 kHz	0.0615 fps/pulse	5.3 mv/ft/sec^2
Rate (X,Y,Z)	12.8 kHz	62 arc-sec/pulse	30 mv/deg/sec

The ISA electronics depicted in Figure 2 comprise the following functions:

- Analog Loop. Maintains the accelerometer pendulum or gyro gimbal at null while providing precision acceleration or angular rate information to the digitizer. The accelerometer loop is integral to the sensor.

- Digitizer. Provides output pulses as a function of the time-integral of the analog loop output voltage.

- Precision Pulser. Provides precision reference pulse train for each digitizer.

- Countdown Logic. Provides precision timing pulses for the precision pulser and digitizers, and provides reference waveforms for the gyro spin motor and signal generator excitation supplies.

* Not a true reset but a "summed" rebalance pulse.

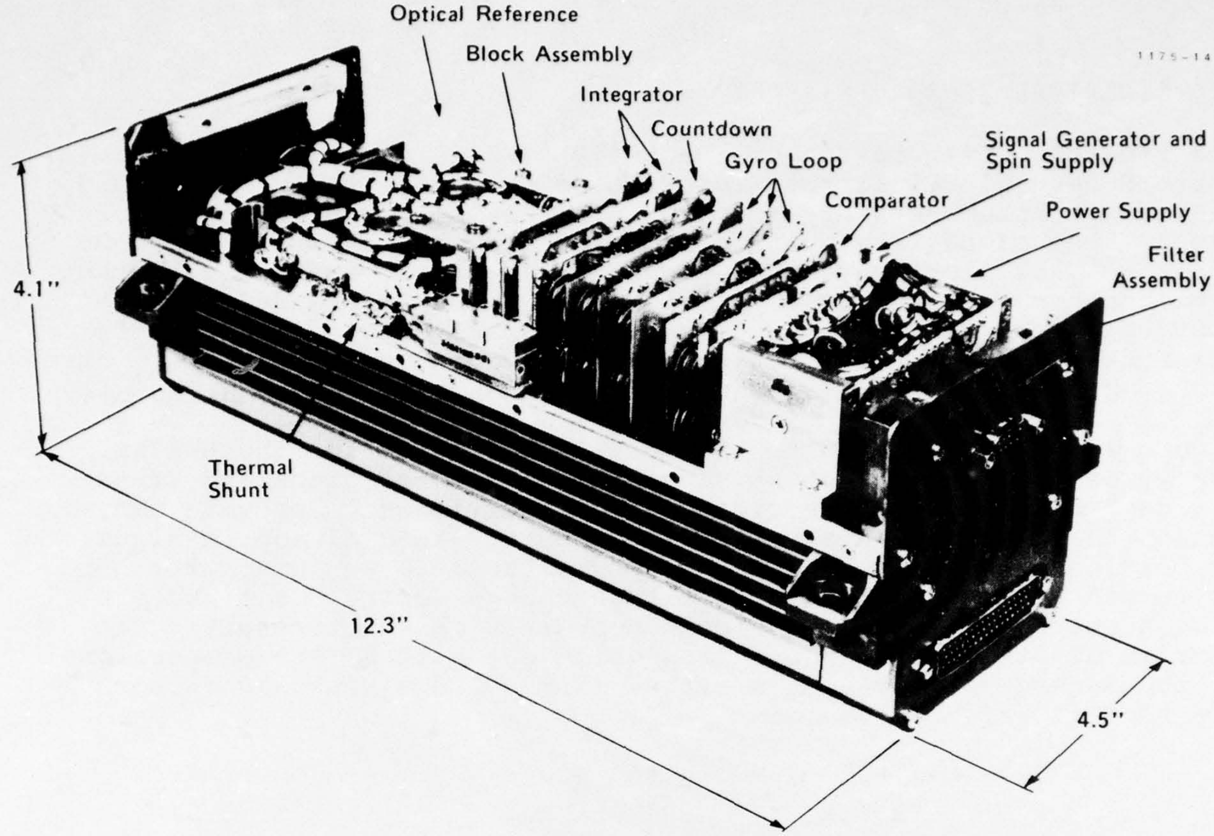


FIGURE 1 **H478F ISA**

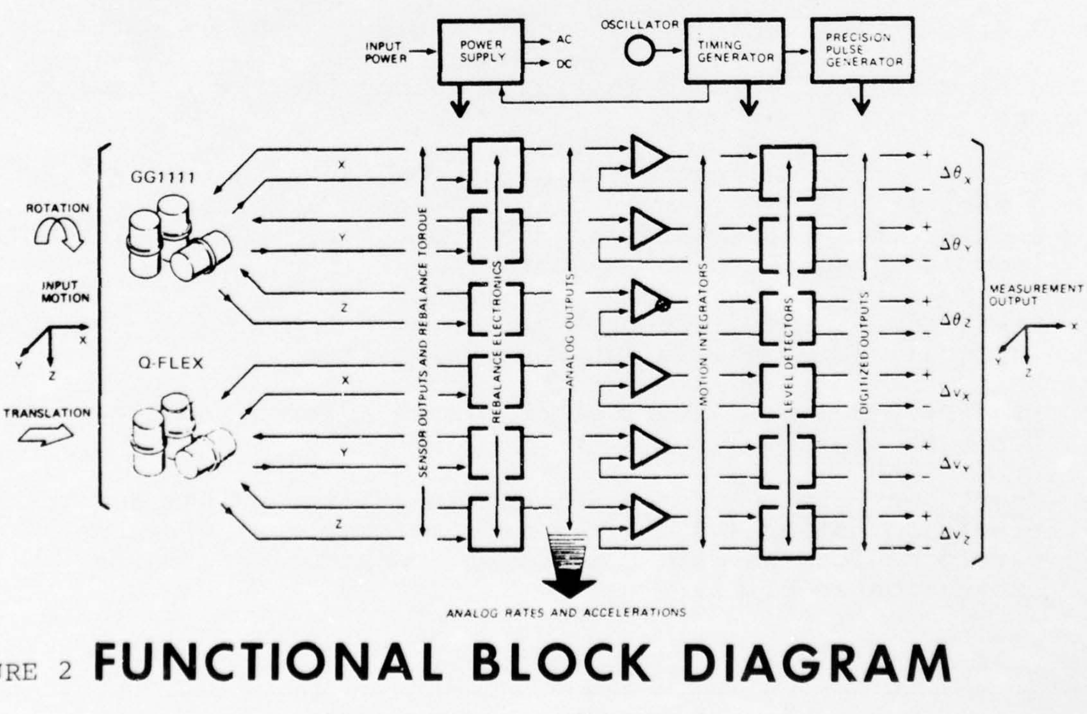


FIGURE 2 **FUNCTIONAL BLOCK DIAGRAM**

* Spin Motor Supply. Provides square wave power to all three synchronous speed gyro spin motors.

* Signal Generator Supply. Provides sinusoidal waveform power for the three gyro signal generators.

* Thermal Control. Controls inertial component block temperature to the degree required to satisfy mission needs.

* DC Power Supply. Provides dc supply voltages for all assemblies except heater power.

Significant fabrication, assembly and test techniques used include:

* Conventional double-sided printed circuit boards.

* Wave soldering of printed circuit assemblies.

* Simplified extruded chassis construction.

* Plug-in boards for ease of electrical test and maintenance.

* Automatic functional acceptance test using a precision Goerz test facility and a Honeywell H-316 computer.

Performance of the ISA depends on the dynamics of the specific application. The performance terms of Figure 3 provide a list of parameters and their specification values which permit the generation of an error analysis for given missions. Alternate sensors also exist which can be used in the H-478F without changing sensor mounting or electrical interface. For example, GG1111 gyros with drift stability of ±1 degree/hour (±2 degree/hour/g) and rate capability of less than 50 degrees/second are available. Alternatively, gyros with rate capability in excess of 400 degrees/second and drift stability of 7 degrees/hour (7 degrees/hour/g) are also available. Accelerometers with a bias of 200 μg can be incorporated into the accelerometer channel if needed for specific applications.

Several sensor options have been employed in the various ISA configurations. However, all configurations of the H-478 family use the same basic construction techniques and electronic circuits. Although the GG8105 ISA for JAE has been repackaged to fit a flat form factor of 20 by 26 by 5.1 cm, the same components and circuits are used. In all configurations, both digital and analog signals are provided to simplify autopilot mechanization and reduce computational processing requirements. The small size and weight of these devices are exploited for tactical weapon applications.

Parameter	Typical Performance Value (3 Sigma)
Gyro Channel (Heated Block)	
Max Continuous Rate	220 degrees/second
G-Insensitive Drift Stability (6 mo)	2 to 4 degrees/hour
G-Insensitive Drift Stability (Continuous Operation)	0.2 to 0.4 degree/hour
G-Sensitive Drift (6 mo) (Vector Sum)	±7 degrees/hour/g max
G-Sensitive Drift (Continuous Operation)	±1 degree/hour/g
Anisoelastic Coefficient	±0.2 degree/hour/g^2
Scale Factor Linearity	±0.1 percent FS (0.02 percent to 10 degrees/second)
Scale Factor Stability (6 mo)	±0.1 percent
Alignment Stability	1 mr wrt Chassis
Frequency Response	$f_n \geq 50$ Hz $0.5 < \zeta < 1.0$
Accel Channel Performance (Heated Block)	
Range	25 g
Bias	±1 mg
Bias Stability (6 mo)	±1 mg
Bias Stability (continuous operation)	10 μg
Cross Coupling	10 by 10^{-6} g/g
Rectification Error	0.075 μg/g
Scale Factor Linearity	0.1 percent FS (0.01 percent to 1 g)
Scale Factor Stability	0.1 percent
Scale Factor Asymmetry	0.05 percent
Frequency Response	> 100 Hz
Alignment Stability	≤ 1 mr wrt Chassis

FIGURE 3. H-478F PERFORMANCE TERMS

3.0 HDC-301 COMPUTER UNIT

The computer configuration shown in Figure 4 is a compact, low power, low cost, general purpose computer currently being applied to the ASM and to other customers. It is a self-contained unit featuring a MOS LSI Central Processing Unit (CPU); three I/O boards, two memory boards, and a power supply housed in an investment cast aluminum chassis. Pertinent characteristics of the computer are shown in Figure 5. The power supply is located in the base of the chassis and is isolated from the digital electronics section by a metal shelf to minimize the effects of EMI. The power supply operates from +28 vdc and provides all power required by the digital electronics and the GG8105 Inertial Sensor Assembly used in the ASM. All other electronics including CPU, I/O and memory, are mounted on 6 standard size printed circuit boards and chassis installed using Birtcher card guides. With the computational speeds shown in Figure 5 the computer provides a throughput capability of approximately 140 kops for a typical avionics software mix. The CPU has 47 instructions, 1 hardware index register, 16 bit parallel DMA (Direct Memory Access), 12 input/10 output discretes, and is TTL compatible at all interface circuits. The HDC-301 CPU (Figure 6) is a standard product which was fully qualified during 1974.

The CPU has been widely used on such programs as Helmet Sight System, F-14 VTAS (Visual Target Acquisition System), digital autopilot flight control system, and Honeywell's Laser Inertial Navigation System (LINS). The CPU is capable of operation with up to 16K instruction memory.

The memory section has four options:

1. Core memory (for software development)
2. Discrete masked ROM for large production
3. One time programmable memory (PROM) for pilot production
4. Electrically alterable memory (EAROM) for semiconductor applications requiring the flexibility of program alterations.

Because semiconductor memory preserves the compact form factor and low power essential to tactical weapons, it is preferred for operational use. Although core memory could be used, it presents a severe size, weight, and power penalty to the device. All the above semiconductor memory options (2-4) are available on multilayer printed circuit boards with approximately 2.8K words per board. These are interchangeable at the board level regardless of semiconductor type selected. Basically the memory capacity per board is as follows.

	Instruction	Constant Data	RAM (Scratchpad)
ROM (masked)	2048 x 16 bit words	512 x 16 bit words	256 x 16 bit words
PROM	2048 x 16 bit words	512 x 16 bit words	256 x 16 bit words
EAROM	2048 x 16 bit words	1024 x 16 bit words	256 x 16 bit words

BG8105 COMPUTER CONFIGURATION

A7510-062

FIGURE 4

Parameter	Characteristic
• Form Factor/Size	BG8105 Configuration 6.6 x 4.5 x 9.0 inches (266 $inches^3$) 16.7 x 11.3 x 22.8 cm (4350 cm^3)
• Weight	9.8 pounds (4.5 kg)
• Power	+28 vdc Supply (35 watts - computer only)
• I/O Section	16 Bit Parallel
• Memory	Semiconductor- PROM (ROM)/RAM 4096 x 16 Bit Instruction 1024 x 16 Bit Constant 512 x 16 Bit RAM
• CPU Fabrication	2 MHz Crystal (Precision Frequency Source) 15 Custom PMOS LSIC (Multiple Sourced) 28 Additional Integrated Circuits 10 Layer PC Board
• Computation Speed	5 μsec Add Single Precision 21 μsec Multiply 65 μsec divide Note: With optional crystal, 40 percent improvement available, i.e., 3.6 μsec add, etc.

FIGURE 5. HDC-301 COMPUTER CHARACTERISTICS

HDC-301 CPU

A7412-167

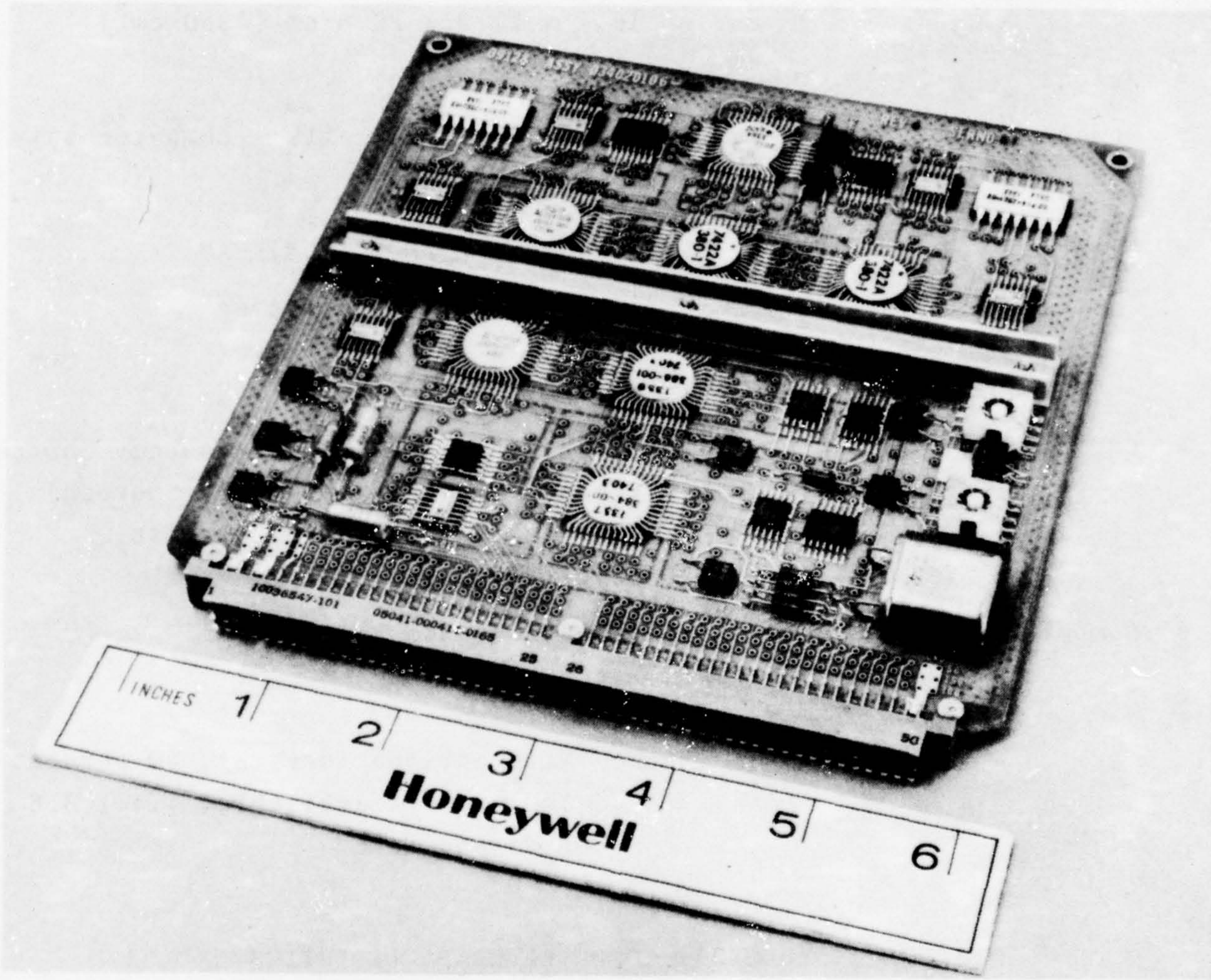


FIGURE 6

The combination of instruction, data, and RAM or volatile memory per board is based on typical application demands and can be altered, if necessary, for other specific mixes. Figure 7 is a picture of a PROM memory board. Both PROM and EAROM memory boards require user instrumentation tooling or "loaders" to modify the contents of memory. Honeywell has designed and uses representative loaders both in the factory and at field sites. Memory alteration times for PROM memory can be achieved in a matter of a few hours including removal of the discrete PROM part from the memory board. EAROM memory can be altered in a few minutes with appropriate loader either at the board level or in the final device configuration.

All Input/Output (I/O) electronics are contained on three separate double-sided printed circuit boards identical in size and mounting characteristics to the CPU and memory boards. Both typical and current ASM I/O functions are listed in Table 2 and a functional diagram of the vehicle or weapon interface is shown in Figure 8.

TABLE 2. I/O FUNCTIONS

Function	ASM I/O	Typical I/O
INPUT:		
Serial Word	Load computer	Load computer
Pulse Counters	Receive 4 channels of inertial data	Receive 6 channels of inertial data; expandable for other data
Analog Input	Homing head and radar altimeter inputs	10 channels available
Input Discrete	Missile staging/release and arm/destruct	12 inputs available
Power Monitor	Orderly power Up/Down	Orderly power Up/Down
OUTPUT:		
Serial Word	(Not included)	Telemetry
Analog Output	10 channels; autopilot, homing head, test	16 channels available
Output Discrete	6; autopilot, homing head, aircraft	Any number easily mechanized
Time Interrupt Frequency	200 Hz	200 Hz

HDC-301 2K PROM MEMORY

A7503-004

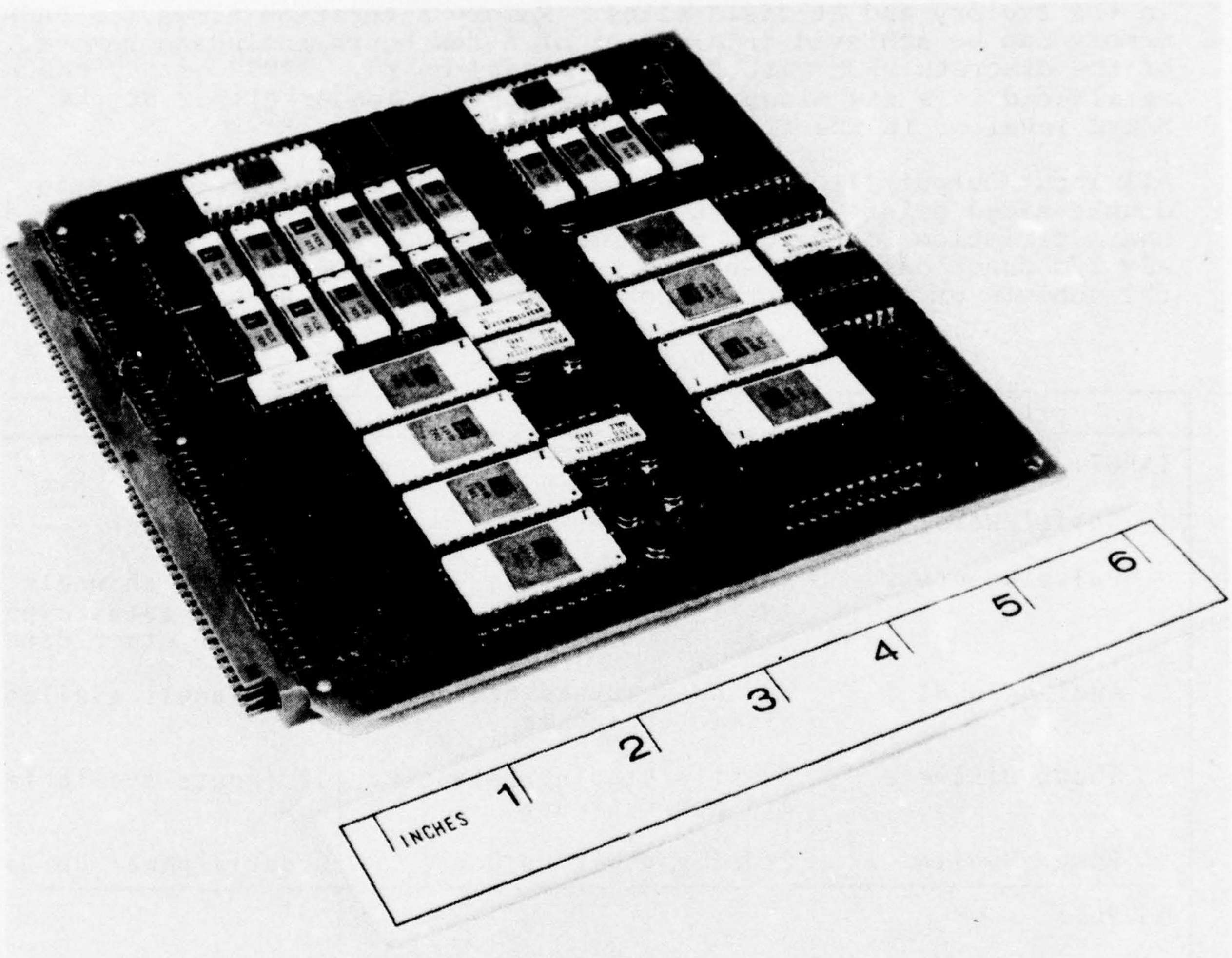


FIGURE 7

TYPICAL HDC-301 I/O FUNCTIONAL BLOCK DIAGRAM

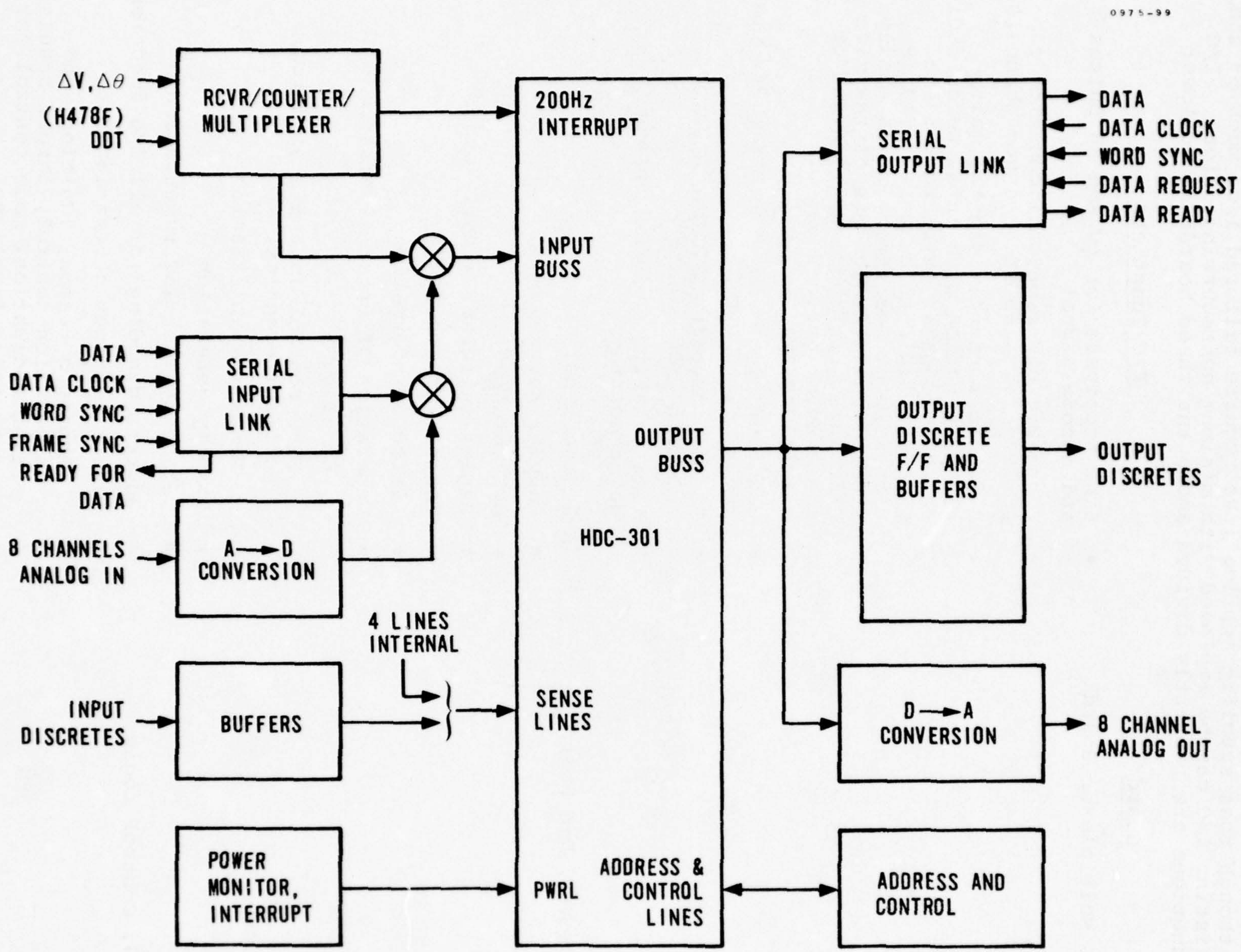


FIGURE 8

Although most specific applications require tailored I/O, much of the existing I/O can be employed with minimum nonrecurring effort. I/O functions are presently divided among the three boards as follows:

Board	I/O Functions
1. Multiplexer Board	• Line receivers for ΔV and $\Delta\theta$ pulses and decode signal • Eight-bit bidirectional counting capability for each of 6 sensor channels • A 16 bit word, 4:1 digital multiplexer function with three words dedicated to counter sampling and one word available as a spare. (Additional input bus expansion is easily accomplished through use of the wire-OR'd input bus configuration and/or addition of another set of multiplexers.) • Countdown logic to generate a 200 pps interrupt to CPU • Address decoding for the counter sampling • Test function for each channel pulse counter
2. A→D, D→A Board	(A→D Functions) • Angular rate • Acceleration • Angles (aircraft gimbal, other) • Target information • Altitude information • Generation of error signals for: Steering Fire control (antenna pointing, optical scanning, etc.) Missile stabilization • Display generation • Telemetry/Test Instrumentation
3. Control Logic	• Address decoding for all I/O functions • Discrete output generation for: Arming a weapon, ignition, and separation control, target acquisition indication, mode control for supporting functions

3. Control Logic (Continued)

- Discrete output generation (Continued)

  Self-test (GO) indication

  Internal I/O control functions

- Control line buffering, fan-out, and fan-in logic

- Power interrupt circuitry to generate an orderly power-up/power-down.

Filtered dc power, at the required voltages for the computer and ISA, is provided by a unique high frequency DC/DC converter. This converter accepts aircraft or missile battery 28 volt dc power through a diode "OR" connection and time-ratio regulates the voltage for use by a high frequency power generator. This power generator produces a square-wave voltage which is converted to the required levels by a small toroidal transformer having multiple secondary windings. Conventional rectifier/filters render the transformed ac power in useful dc form.

Excellent thermal and EMI control has been achieved by locating the power supply in the base of the computer and maintaining a bulkhead between the power supply and the other circuits of the computer.

In summary, the HDC-301 offers a compact configuration with low weight, size, and power. In addition, it features versatile and easily applied memory options and common I/O functions which are easily adapted to specific tactical weapon requirements.

4.0 SOFTWARE

Software is the generic name used to describe the programs, routines, codes, and other written information used with digital computers as distinguished from the actual devices or "hardware". Honeywell has a complete set of software (S/W) tools for program development or adaptation including an HDC-301 users manual, an assembler, simulators, utility subroutines, and I/O test programs. In addition, S/W to test the CPU, memory boards, I/O, flight software, and to calibrate and test the ISA has been developed. Only the application dependent I/O S/W requires modification for new applications.

A complete library of operational software modules is available for specific missions. The following list comprises the most commonly used software modules for tactical Guidance and Control:

<u>Input Related Software</u>

Initialization

- Target Data Input
- Sensor Compensation Input
- Attitude Input
- Position and Velocity Input
- Initial Mode and Timing Input
- Parity Processing Input
- Conversion to Internal Program Parameters

Alignment

- Transfer (Velocity Match Alignment to aircraft navigator)
- Ground Gyrocompass
- Fixed Position Update

<u>Flight/Operational Processing</u>

- Sensor Input Processing (inertial or special)
- Strapdown Coordinate Transformation
- Navigation
- Guidance and Steering
- Flight Control (application dependent)
- Attitude Maintenance
- TM Signal Processing
- Self-Test Timing Generation

<u>Output Related Software</u>

- Special Devices (Homing head scanning, discrete outputs, staging, etc.)
- TM Outputs
- Steering Outputs
- Self-Test Output

The listed software modules for the H-478F/HDC-301 have been augmented with 5-state, 8-state, and 12-state Kalman filters for specific applications. Velocity matching alignment to master navigator is a key software function that permits fast reaction time essential to many tactical weapons deployment.

5.0 ENVIRONMENTAL

The H-478/HDC-301 Inertial system was basically designed to meet MIL-E-5400 Class 1A equipment. Development evolution and customer requirements have expanded the environmental capacity of the system. Table 3 summarizes the environmental characteristics of the system.

TABLE 3. ENVIRONMENTAL CHARACTERISTICS

Environment Environment	H-478F	HDC-301 (BG8105 Configuration)
Vibration	10 grms 20-2000 Hz random	7.6 grms 20-2000 Hz random 10g-pk 20-2000 Hz sinusoidal
Temperature	-40 to +145°F (Operation to +160°F possible with performance relaxation)	-31 to +160°F
Altitude	70,000 feet	70,000 feet
Shock	20g, 11 ms, half sine (operating)	20g, 11 ms, half sine (operating)
EMI	Per MIL-STD-461A Notice 3 for Class 1D Equipment	Per MIL-STD-461A Notice 3 for Class 1D Equipment
Humidity	95 percent minimum	95 percent minimum

6.0 RELIABILITY

Established reliability parts are used in both the ISA and computer unit, e.g., microcircuits per MIL-STD 883 Class B or better, semiconductors per JANTX or better, resistors per MIL-STD 199 minimum established failure rate or better and capacitors per MIL-STD 198 "P" failure rate or better. Reliability assessment for fixed ground environment per MIL-HDBK-217B is shown in Table 4.

TABLE 4. RELIABILITY ASSESSMENT

Assembly	Subassembly	Failure Rate ($F/10^6$ Hours)	MTBF (Hour)
H-478F ISA	GG1111 Gyro (X3)	172.8	
	Q Flex Accel (X3)	75.0	
	Power Supply	3.6	
	Remaining Electronic	31.7	
		283.1	3532
BG8105 Computer	Power Supply	3.6	
	I/O Boards	64.5	
	CPU (HDC-301)	31.6	
	Memory	42.7	
	Chassis	78.2	
		220.6	4532

Actual experience with flight hardware has shown that eleven H-478 devices experienced 3500 field hours on the SHAG program without a chargeable failure. To demonstrate the reliability of the HDC-301, five processors were subjected to 1,000 hours of operation at 125°C. Although calculated failure rate data indicated four LSIC failures should have occurred, none were experienced.

7.0 SUPPORT EQUIPMENT

To enhance user checkout and application of the H-478/HDC-301 Inertial System, Honeywell has developed the support equipment shown in Table 5.

TABLE 5. SUPPORT EQUIPMENT*

Item	Function
System Test Panel	Tests either ISA or computer or both Note: Modifications are probably required to tailor the panel to specific applications.
Computer Control Unit (CCU)	Control and communication interface between computer and operator; provides control and display functions including teletype.
Memory Interface Board (MIB)	Interfaces computer with core memory in place of flight memory and allows special test software diagnostics to be used during computer checkout.
Memory Loader Two Types: 1. PROM 2. EAROM	Permit alteration of semiconductor memory.

*It is assumed that the customer would supplement this special purpose test equipment with appropriate peripherals and standard lab equipment to satisfy specific applications.

8.0 SUMMARY

Physical features and performance characteristics of the H-478/HDC-301 Inertial System make it a suitable candidate for the guidance and control functions in tactical weapons. Current development status assures that these applications are low risk. Availability of existing software modules and supporting support equipment eliminates substantial nonrecurring effort in support of specific applications.

Figure 9 is a table identifying the error sources and sensitivities for tactical missile analysis assuming an all inertial control system, i.e., no terminal seeker. Using Figure 9 and the sensor error terms listed in Section, Figure 3, the following air-launched, tactical-missile, error assessment can be made:

Assumptions:

180 second flight
80 nautical mile range
Velocity match alignment providing initial conditions of:

±0.5 nm position
±2 fps velocity
±0.5 degree azimuth
±0.5 degree roll

$\Delta V \approx 2000$ fps

Error Analysis:

Source	Value (3 Sigma)	Cross Course Error Velocity Ft/Sec	Cross Course Error Position Ft
Initial Position	3000 ft	0	3000
Initial Velocity	2 fps	2	360
Initial Azimuth	1.7 mr	3.4	610
Initial Roll	1.7 mr	9.8	890
Roll Drift	3 degree/hour	7.6	455
Roll MUSA	6 degree/hour/g	10.5	904
Accel Bias	1 mg	5.8	520
	RSS	17.7	3413

Source	Units	Units Conversion Factor	Cross Course Sensitivity: Velocity (Ft/Sec)	Cross Course Sensitivity: Position (Ft)
Initial or Position	Ft	1	0	1
Initial or Velocity	Ft/Sec	1	1	T
Initial Azimuth	MR	0.001	ΔV	ΔV T
Initial Roll	MR	0.001	G T	$1/2\ G\ T^2$
Roll Drift	Deg/Hr	4.848×10^{-6}	$1/2\ G\ T^2$	$1/6\ G\ T^3$
Roll MUSA	Deg/Hr/G	4.848×10^{-6}	ΔV T	$1/2\ \Delta V\ T^2$
Cr Accel Bias	Mili-g	0.001	G T	$1/2\ G\ T^2$

Source Value x Unit Conversion Factor x Sensitivity = Error

T Time (Seconds)

G Gravity (32.2 Ft/Sec^2)

ΔV Initial Velocity Change (Ft/Sec)

FIGURE 9. SIMPLIFIED MISSILE ANALYSIS (T < 10 MIN)

If errors in the pure inertial mode preclude the mission objective, then a terminal seeker may have to be added. The subsequent error analysis would have to contrast the cr-ss range RSS with the seeker acquisition basket. With this type of analysis, an interested user can examine the applicability of the H-478/301 system to specific applications.

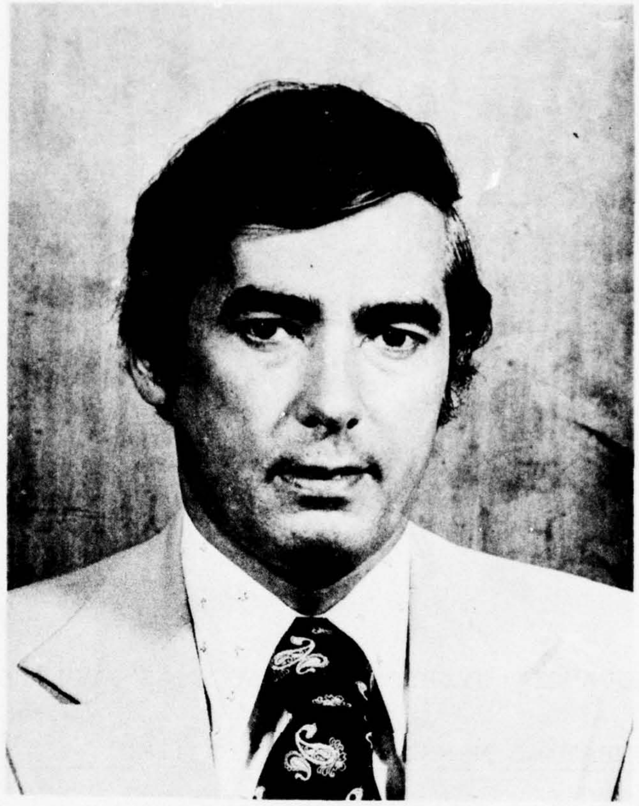
Honeywell is confident that the H-478/HDC-301 system can be a satisfactory solution to a variety of guidance and control problems involved in tactical weapon development, production, and deployment.

ACKNOWLEDGEMENTS

The author appreciates the support received from the Honeywell engineers and staff personnel who participated in the design and development of the H-478 Inertial Sensor Assembly and the HDC-301 computer, especially L. P. Ball - ASM Program Manager, Les Newberry, ASM I/O Designer, and John Kuslich - ASM Power Supply Designer, and Avery Morgan - G&C StaffEngineer. It was the generous support of these people that made possible the compilation of the detail in this paper.

BRIEFING TITLE

USE OF ADVANCED HYBRID TECHNOLOGY IN AN IMU



FRANK PETKUNAS

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THE USE OF ADVANCED HYBRID TECHNOLOGY AS APPLIED TO AN INERTIAL MEASUREMENT UNIT (IMU)

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INTRODUCTION

The rationale for choosing a particular packaging technique for any system is always dependent on the fixed parameters of the system. In cases where there is ample volume and weight, many schemes can be considered from which the cheapest and most reliable design can be chosen. In cases where there are severe limitations on volume, weight, and interconnect capacity yet a high reliability factor is required, the number of viable alternatives becomes reduced and newer technologies and techniques must be employed.

In the case of the AIRS (Advanced Inertial Reference Sphere) inertial guidance system there were limitations that made conventional packaging virtually impossible. The simple communication system of essentially a single physical line obviated the need for packaging the electronics within the IMU (Figure 1). At the same time, neutral buoyancy and a precise center of gravity of the IMU was essential thus limiting the flexibility on materials selection and structural geometries. Since the system was initially developed for missile applications, it was desirable to minimize the overall volume and the basic sphere size was, therefore, defined as that which would mechanically house the six instruments. The available volume then for electronics resulted in nine major irregular volume envelopes as depicted in Figure 2.

DESIGN APPROACH

In an attempt to maximize overall testing and maintenance at both the subsystem and system level, each electronic assembly would be designed to be independent in terms of electrical and mechanical interfaces; i.e., each electronics block would contain complete testable electronic functions and be immediately removable from the system without hard wire disconnect.

In pursuit of these goals, design studies and iterations were made with thorough considerations of all of the parameters indicated on Figure 3. The results of which were (Figure 4):

1) Volume,weight, and interconnect limitations mandated the use of hybrid technology.

2) Standard and regular geometries could not be used due to the high component density.

3) The interfacing of all electronic assemblies could be accomplished with connectors.

An illustration of the volume reducing power of hybrid microelectronics is shown in Figure 5. There is an estimated volume and weight savings of eight to twelve to one. The general packaging concept that evolved from the engineering studies appears in Figure 6.

AIRS ELECTRONIC HARDWARE

The major concern as with most high-density electronic systems was the overall interwiring scheme between modules and major assemblies within the system. The design philosophy chosen was to keep the wiring external to the modules as simple as possible by preassigning signal locations at the module level and using a simple lateral interwiring system through the use of multiple but identical flextapes and a vertical communications link by a single layer wiring array (Figure 7). The system level interwiring could be accomplished through the use of annular multilayer boards installed in each major cavity with top surface pads as the interface areas for mating with the connectors on the major electronic assemblies.

The simplification of the system interwiring system by preassigning signals at the terminals of all hybrid modules necessitated the ability to have infinite unscrambling power at the module level. This was achieved by using a five layer thick film mother board interwiring system for each module (Figure 8).

The multilayer substrates were fabricated from raw stock of 0.030" 94% fired alumina on which conductors, interconnect vias, and dielectric layers were deposited by concentrated thick film multiple screening and firing processing.

A typical sequence is shown in Figure 9 . These boards are the nucleus for the AIRS hybrid modular system.

The general hybrid module concept for the AIRS system can essentially be described as groups of separate hybrid subunits mounted and integrated on thick film MLB's. A typical module is shown in Figure 10. The engineering rationale for the particular technique is that each subunit can be individually inspected, tested, burned-in, etc., before integration at a higher and more costly level of assembly, the object being to identify all marginal and bad devices at the subunit level where the impact of repair and/or scrap is minimal. Figure 11 illustrates a typical subunit mounted for test. A typical assembly processing sequence is shown in Figure 12. Any causes for rejecting completed modules then are solely due to handling and process damage during the assembly phase of integrating the subunits through the module level. The yield on subunits was characteristically 92% alowing some rework with about 30% of the subunits started being recycled for rework. It is important to note, however, that the acceptance criteria for AIRS hybrid units is extensive and rigid including tight process controls and visual requirements as well as performance specifications. Many of the reworked units were recycled for refinements such as a second cleaning, scratched pad, insufficient bonding fillet, etc., and were not catastrophic rejections.

The yield on integrating subunits to MLB's to complete modules was approximately 86%, the causes for rejection being primarily mechanical and/or visual defects.

A most critical element of the hardware phase of the AIRS Program was the specification, purchasing, and acceptance of electrical components. Components were purchased from various vendors to formal Source Control Documents (SCD's) which were a combination of the vendor's specifications, any special requirements and military standards such as visual inspection criteria as in MIL-STD-883. Lots were accepted on a twenty-five piece sampling plan whereby a single failure of any electrical parameter was cause for rejection of the lot. All chips were 100% visually inspected for MIL-STD 883 B criteria before release to the fabrication area (Figure 13).

It is important to emphasize that historical experience in fabricating hybrid systems of all types and complexities has indicated that it is absolutely essential to develop and confirm formal process specifications and procedures and to maintain discipline in adhering to them throughout all phases of fabrication.

The potential problem of conductive particle contamination such as mobile solder balls and stray wire bond tails was recognized, addressed, and countermeasured through the use

of an aromatic organic conformal coating, monochloropolypara-xylylene, for which the trade name is "Parylene C". The compound is basically a linear polymer of chlorinated xylene molecules deposited from a dimer which is sublimed, energized in a reactor, and deposited as a continuous film at room temperature. The process is licensed by Union Carbide and is functionally described by Figure 14. The coating has infinite and uniform deposition coverage and was found to entrap and immobilize particles. A thorough and adequate thickness coverage was found to be 0.0006". The polymerized compound is basically inert to all solvents but will oxidize at temperatures at or about 100°C and begin to lose strength, craze, and peel. In a nitrogen ambient, however, the stability is much higher.

Examples of AIRS modules are depicted in Figures 15a &b. Again, the reason for the unconventional configurations is due to circuit density. Wherever possible, rectangular geometries were used. In simpler systems where standard packages are feasible, it is recognized that standardization and commonality are prime goals, and a concentrated effort towards simplicity and redundancy should be made.

A summary of the electronic elements comprising the AIRS system is shown in Figure 16. A good deal of redundancy

was sought and achieved in cases where circuitry was repetitive as in the case of electronics associated with the three accelerometers and gyros. For single occurring circuits such as power supplies, monitors, wheel drivers, timing, etc., the electronic assemblies are, of course, unique.

CONCLUSIONS

The electronics for the AIRS stable member were packaged using thin and thick film hybrid technology because of weight and volume constraints. The key to high yield and reliability was found to be: an overall design based on proven design guidelines, complete functional checkout at sublevels of assembly, strict discipline and adherence to a formal set of process specifications, and rigid purchasing and acceptance criteria for all devices and materials.

To date, the AIRS engineering model has more than 4400 cumulative operating hours and the first flight system over 2300. Both systems have been essentially void of hybrid circuit failures, and the replacement and maintainability factors have proven to be extremely favorable due to the simple connector interfacing of the major electronic assemblies.

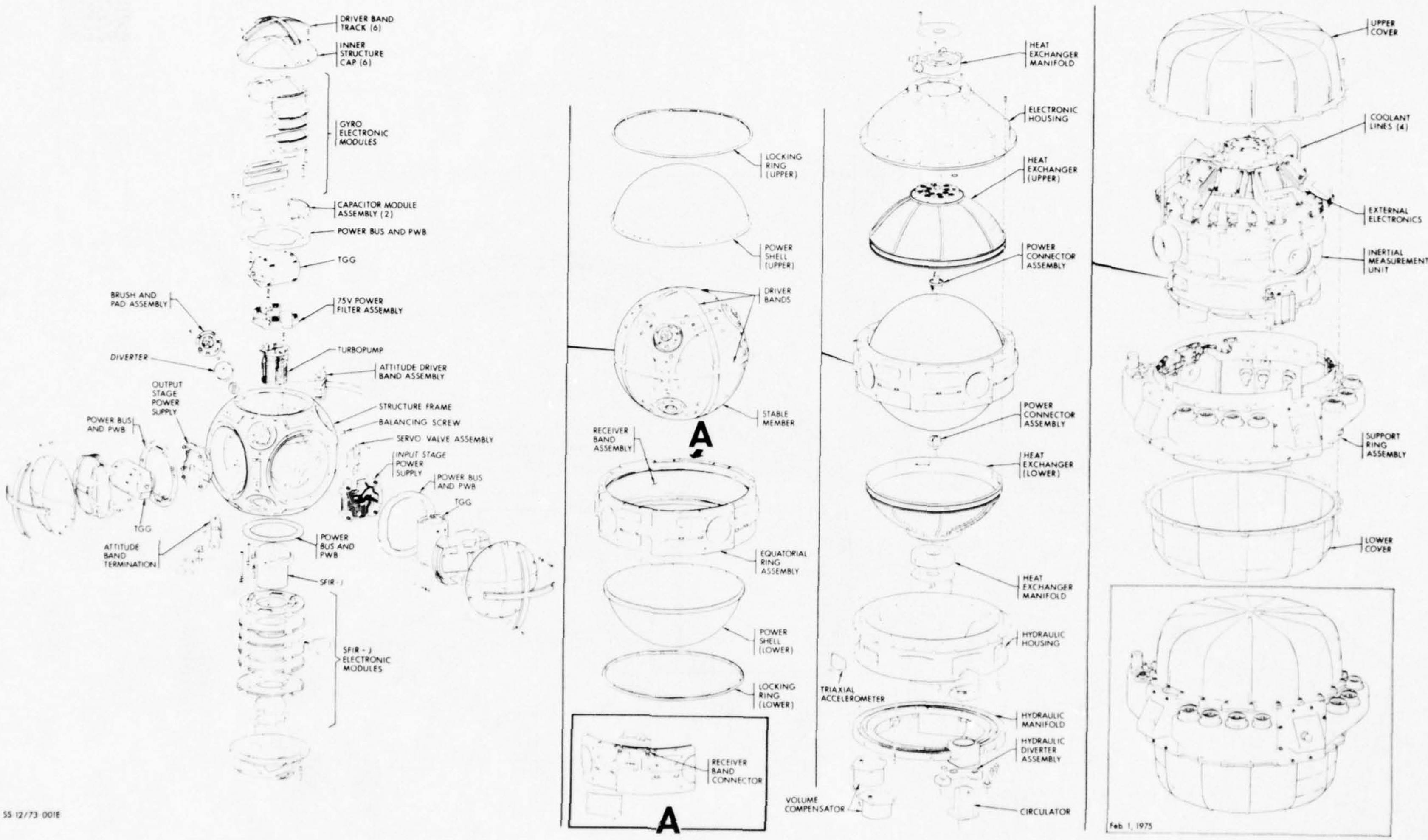
It is, therefore, concluded that hybrid microelectronics can truly make a major contribution to advanced electronic systems where a premium on weight and volume exists. Yield, performance, maintainability, and reliability have been verified to the extent that hybrid circuits for military systems are indeed a reality.

HYBRIDS IN FUTURE SYSTEMS

There are many electronic systems that do not have the conical and spherical geometries as dictated by the AIRS system. Many systems, for example, are employing the Naval Avionics Facility, Indianapolis, (NAFI) packaging concept whereby structures, frames, and connectors are standard and proven pieces of hardware available in various dimensional integrals to which discrete electronic components are mounted (Figure 17). Such a condition represents an ideal case for applying advanced technology to an existing and proven concept in the interest of achieving reliability, commonality, and cost effectiveness. Figure 18 represents an example of what a NAFI card might look like if hybrid microelectronics were adopted and integrated into a NAFI System. It is estimated that eight to twelve conventional discrete component cards could be replaced with a single hybrid card.

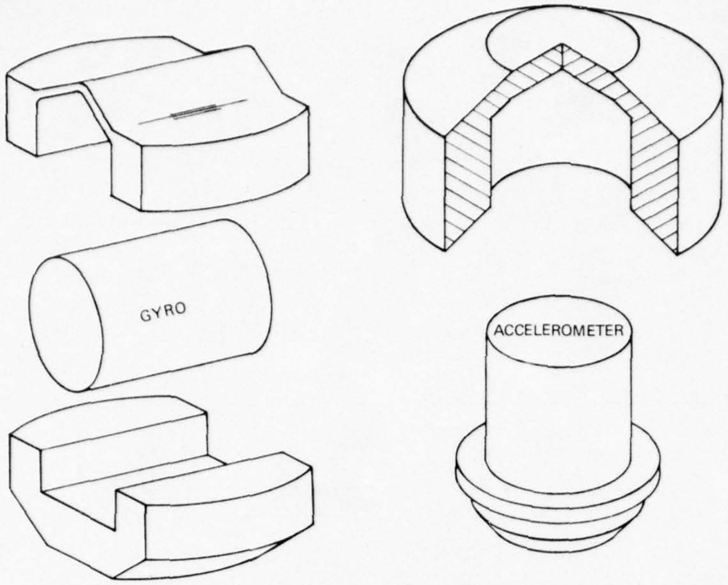
MPMS / AIRS

ADVANCED INERTIAL REFERENCE SPHERE

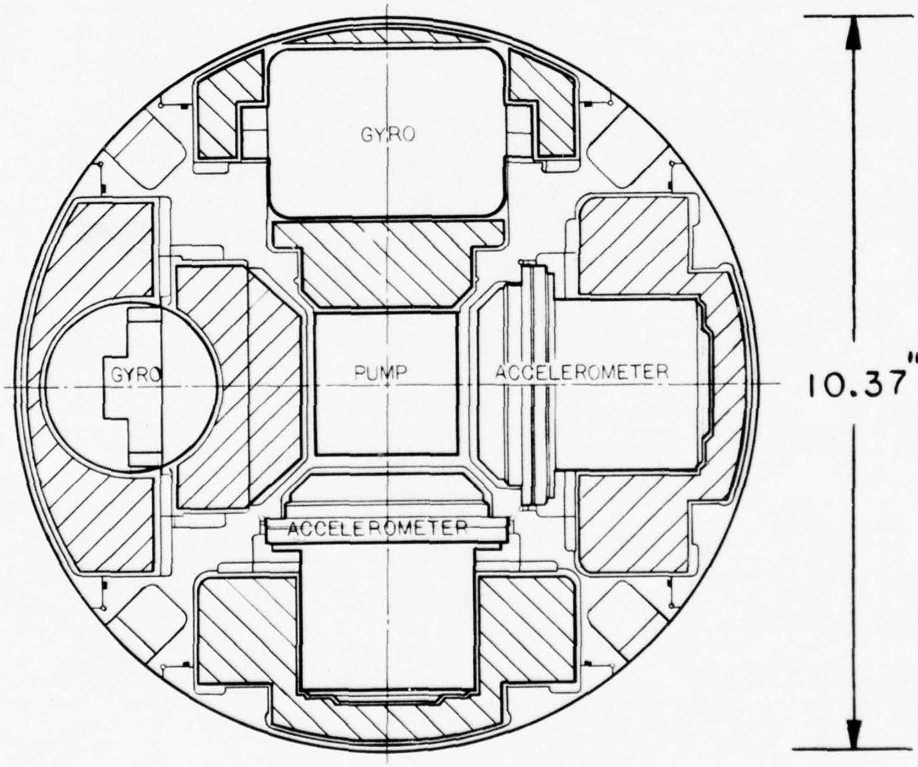


The Charles Stark Draper Laboratory, Inc.

FIGURE 1



AIRS– VOLUME ENVELOPES FOR ELECTRONICS



AIRS– VOLUME ENVELOPE

FIGURE 2

The
Charles Stark Draper
Laboratory, Inc.

SIMULTANEOUS CONSIDERATIONS WHEN DESIGNING A SYSTEM

PHYSICAL	INTERFACING	FABRICATION	ENVIRONMENTAL
MECHANICAL	SIZE	STANDARDIZATION	TEMPERATURE
THERMAL	WEIGHT	YIELD	VIBRATION
AREA ESTIMATES	CONNECTORS	RELIABILITY	SHOCK
CIRCUIT CONSTRAINTS	MOUNTS	COST	RADIATION

The Charles Stark Draper Laboratory, Inc.

FIGURE 3

CONCLUSIONS FROM CONCEPT STUDIES

1) VOLUME, WEIGHT, AND INTERCONNECT LIMITATIONS MANDATED THE USE OF HYBRID TECHNOLOGY.

2) STANDARD AND REGULAR GEOMETRIES COULD NOT BE USED DUE TO THE HIGH COMPONENT DENSITY.

3) THE INTERFACING OF ALL ELECTRONIC ASSEMBLIES COULD BE ACCOMPLISHED WITH CONNECTORS.

The Charles Stark Draper Laboratory, Inc.

FIGURE 4

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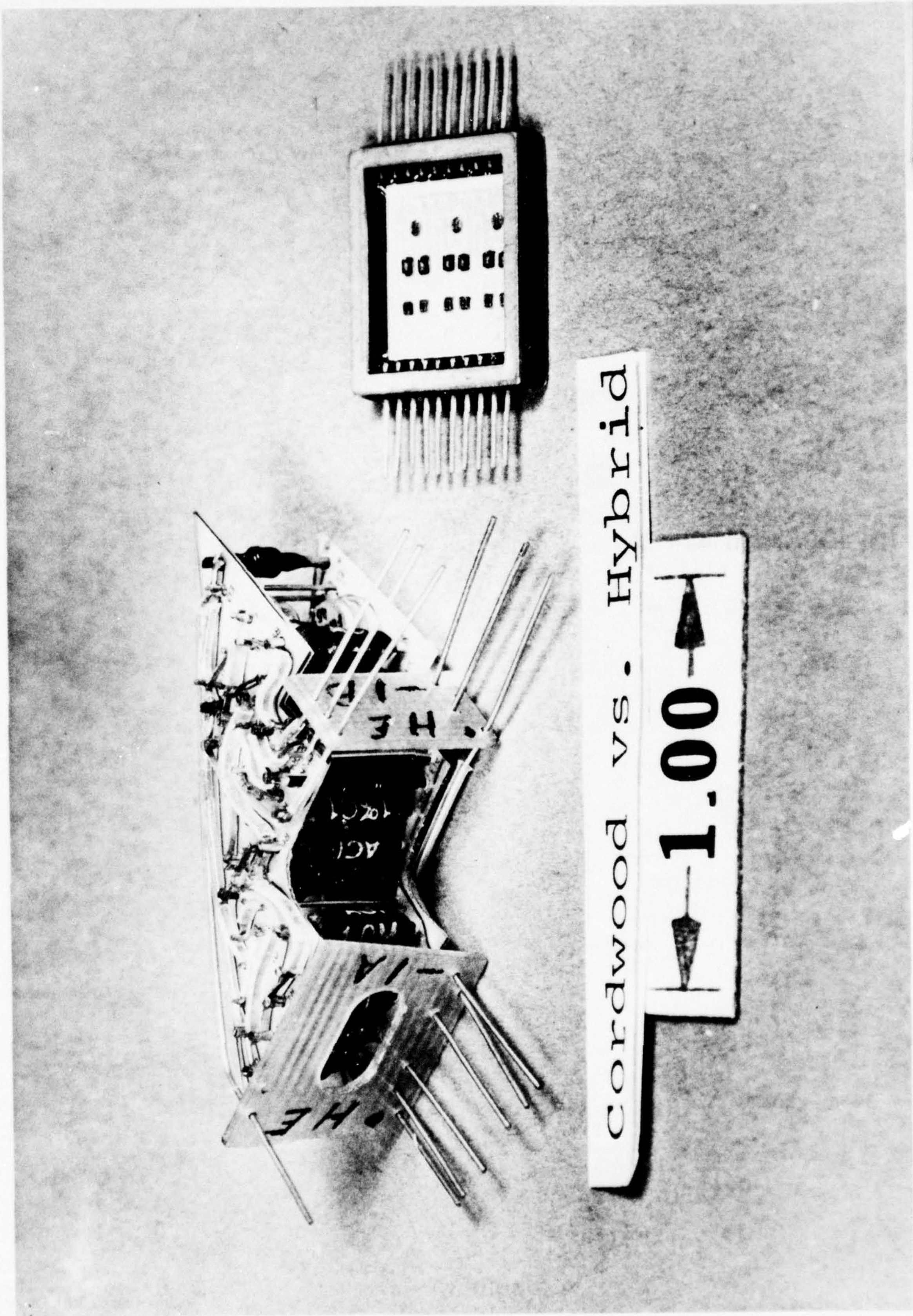


FIGURE 5

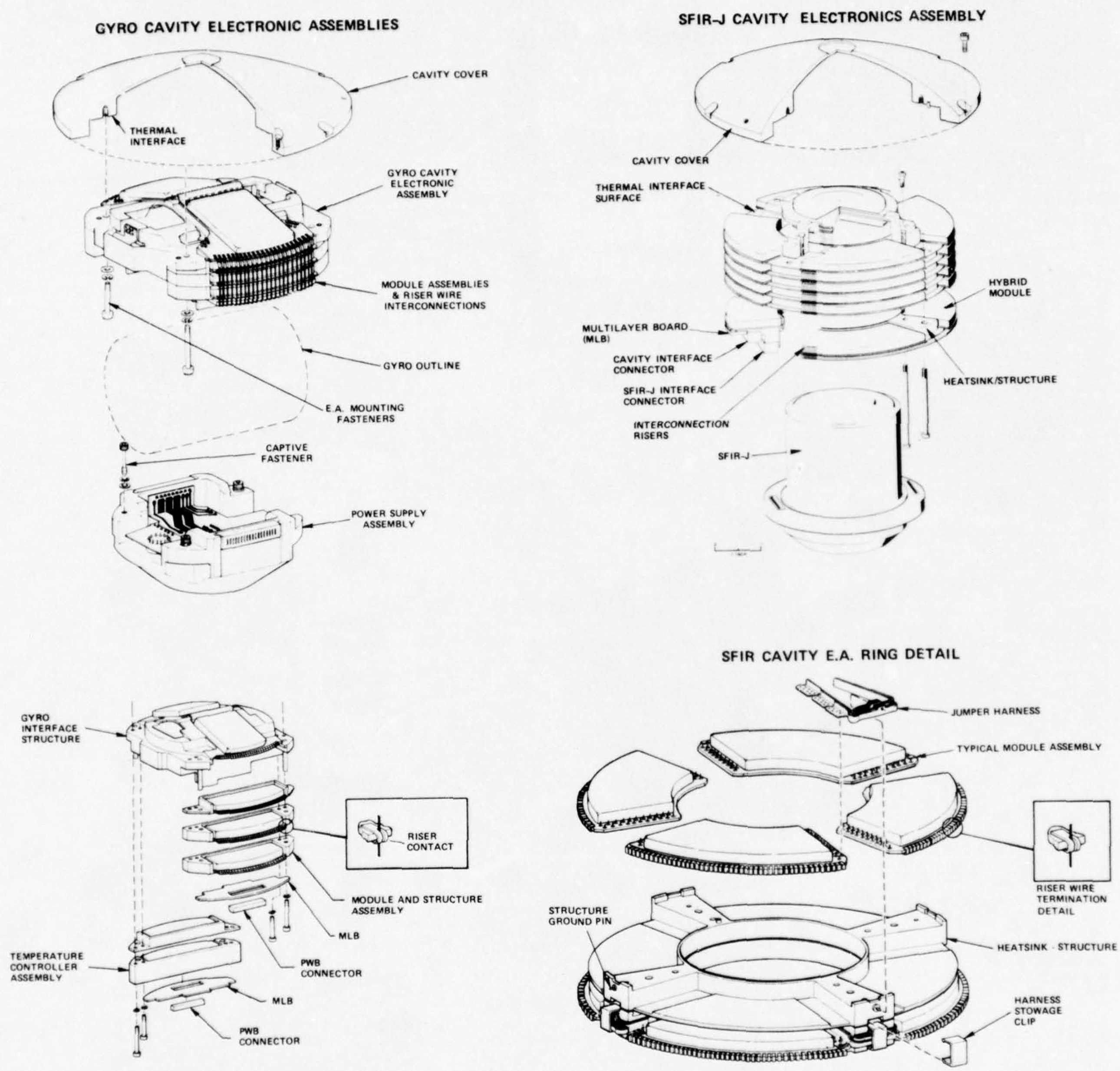
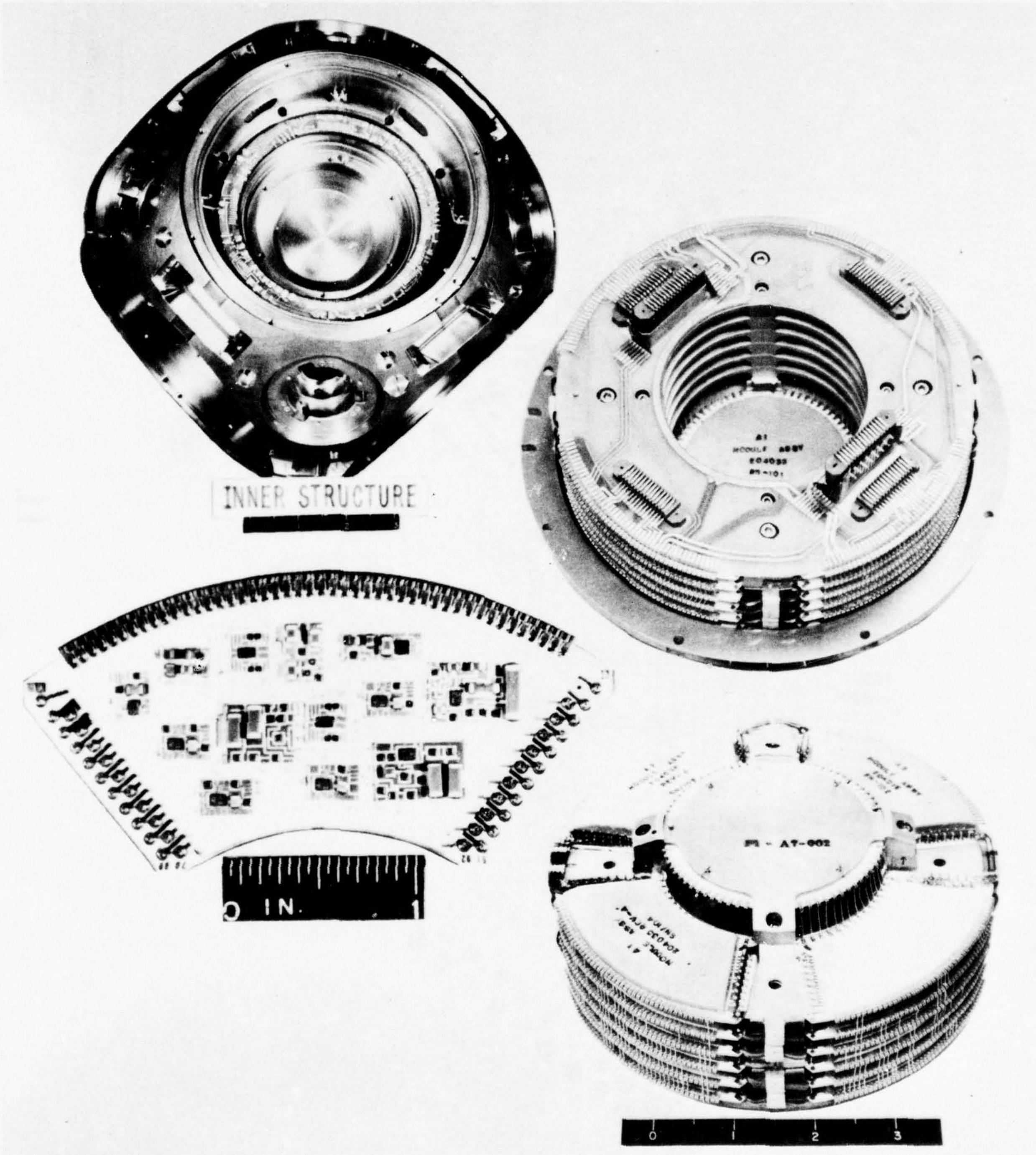


FIGURE 6

The
Charles Stark Draper
Laboratory, Inc.



AIRS Electronic Assemblies

FIGURE 7

X - RAY OF MULTILAYER BOARD

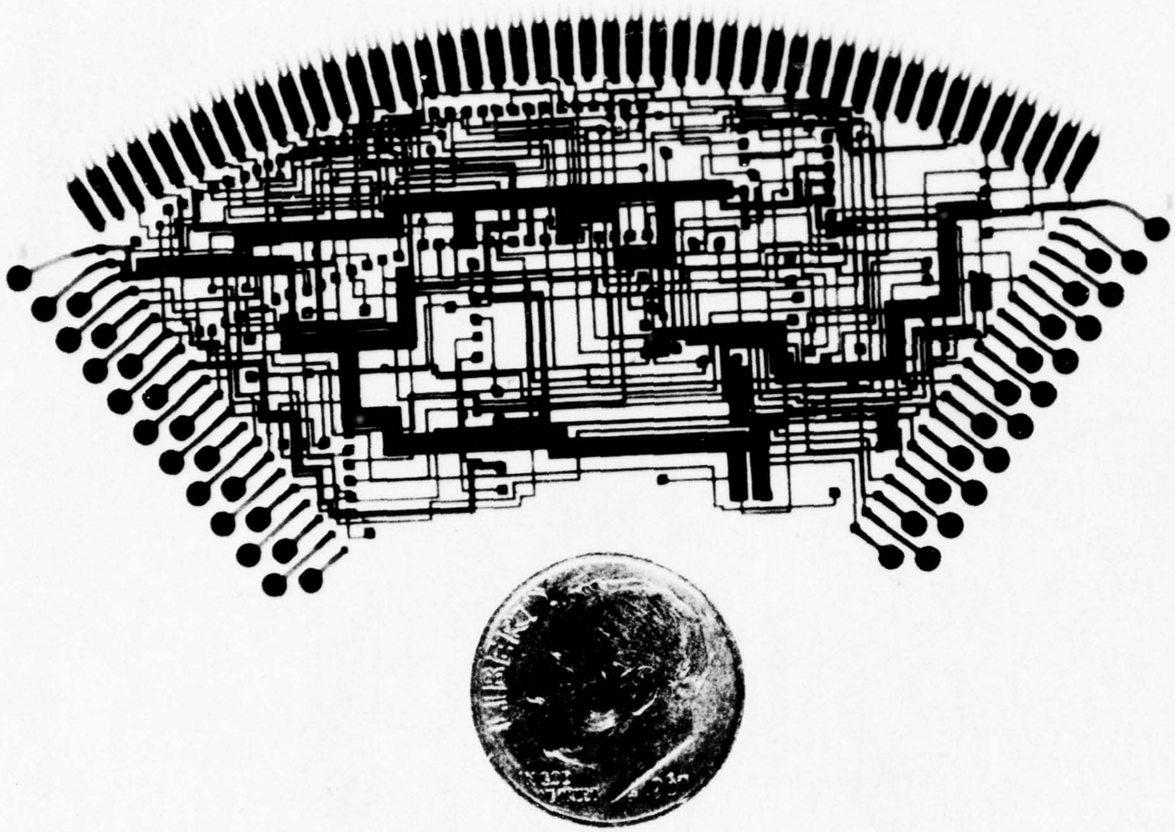


FIGURE 8

The
Charles Stark Draper
Laboratory, Inc.

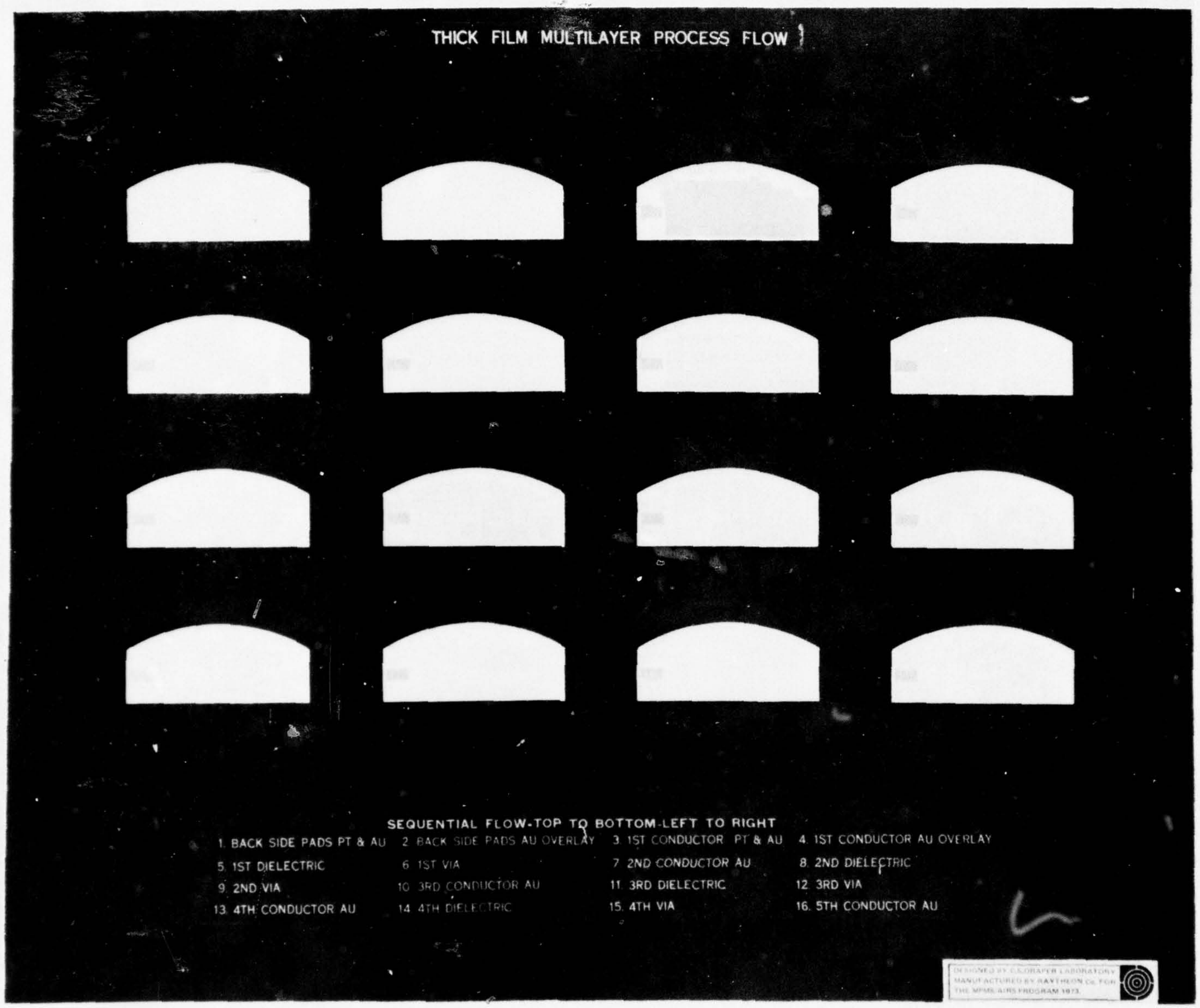
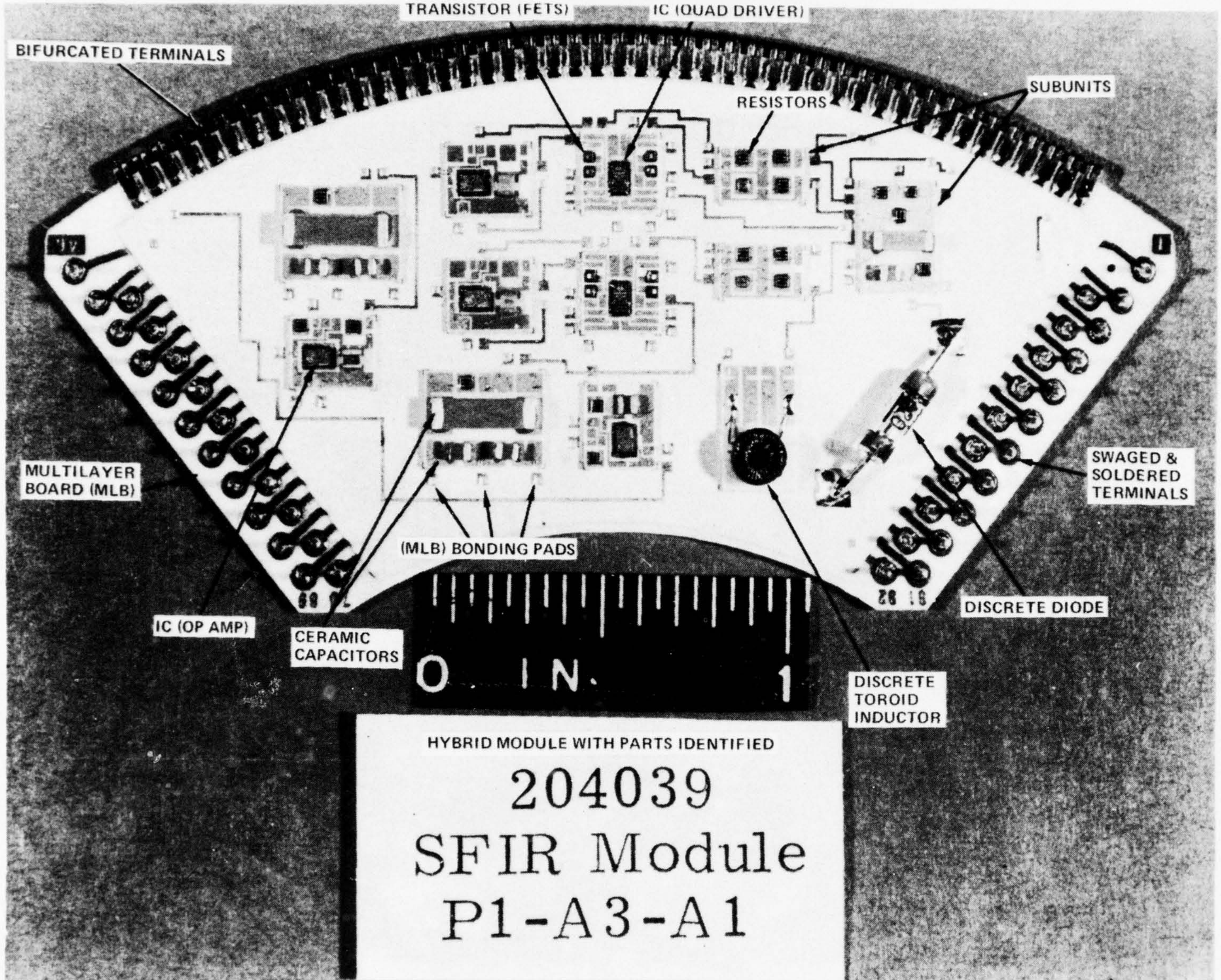
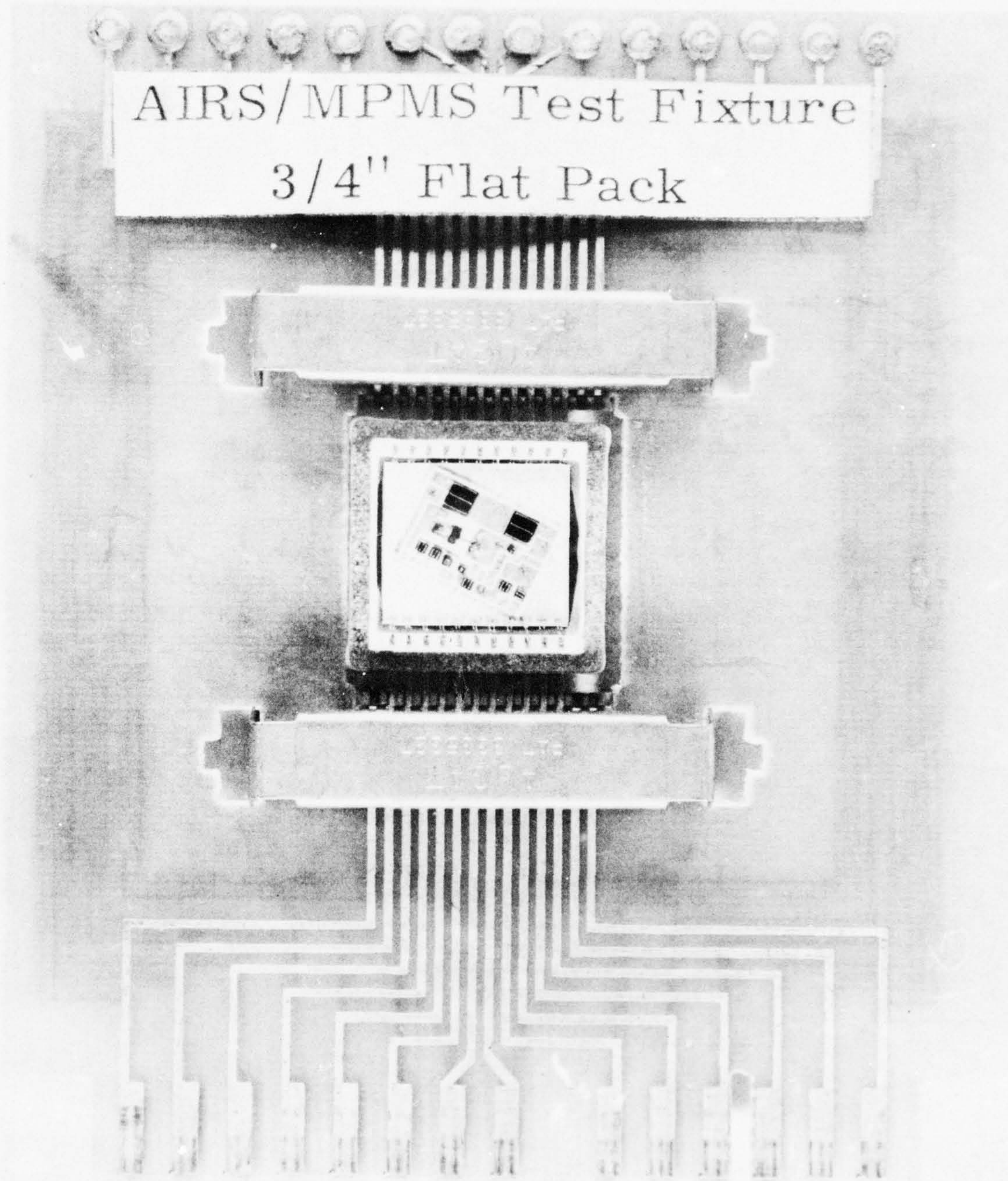

THICK FILM MULTILAYER PROCESS FLOW
SEQUENTIAL FLOW-TOP TO BOTTOM-LEFT TO RIGHT
1. BACK SIDE PADS PT & AU
2. BACK SIDE PADS AU OVERLAY
3. 1ST CONDUCTOR PT & AU
4. 1ST CONDUCTOR AU OVERLAY
5. 1ST DIELECTRIC
6. 1ST VIA
7. 2ND CONDUCTOR AU
8. 2ND DIELECTRIC
9. 2ND VIA
10. 3RD CONDUCTOR AU
11. 3RD DIELECTRIC
12. 3RD VIA
13. 4TH CONDUCTOR AU
14. 4TH DIELECTRIC
15. 4TH VIA
16. 5TH CONDUCTOR AU

FIGURE 9



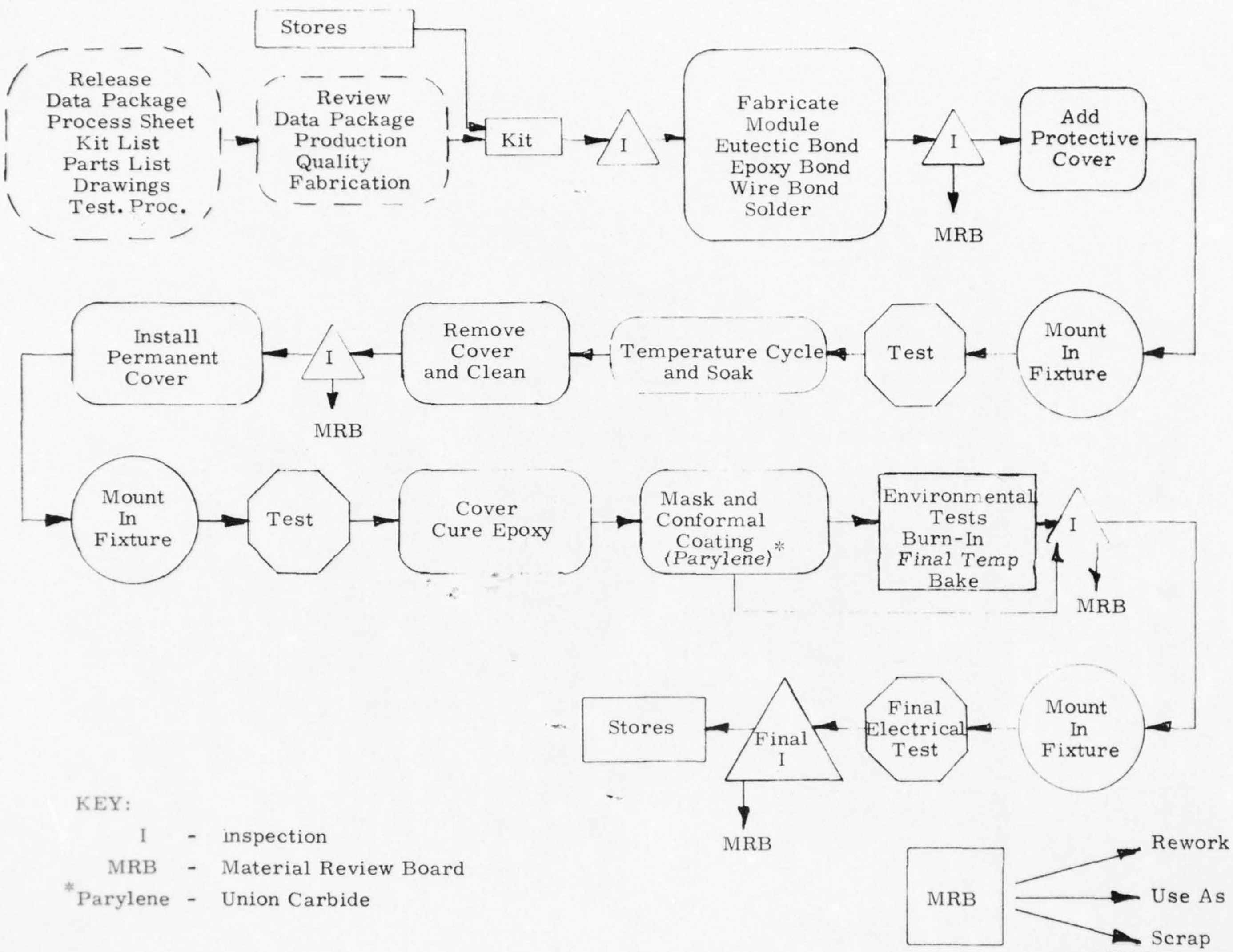
TRANSISTOR (FETS)
IC (QUAD DRIVER)
BIFURCATED TERMINALS
SUBUNITS
RESISTORS
MULTILAYER BOARD (MLB)
SWAGED & SOLDERED TERMINALS
(MLB) BONDING PADS
IC (OP AMP)
CERAMIC CAPACITORS
DISCRETE DIODE
DISCRETE TOROID INDUCTOR
0 IN. 1
HYBRID MODULE WITH PARTS IDENTIFIED
204039
SFIR Module
P1-A3-A1

Figure 10



The Charles Stark Draper Laboratory, Inc.

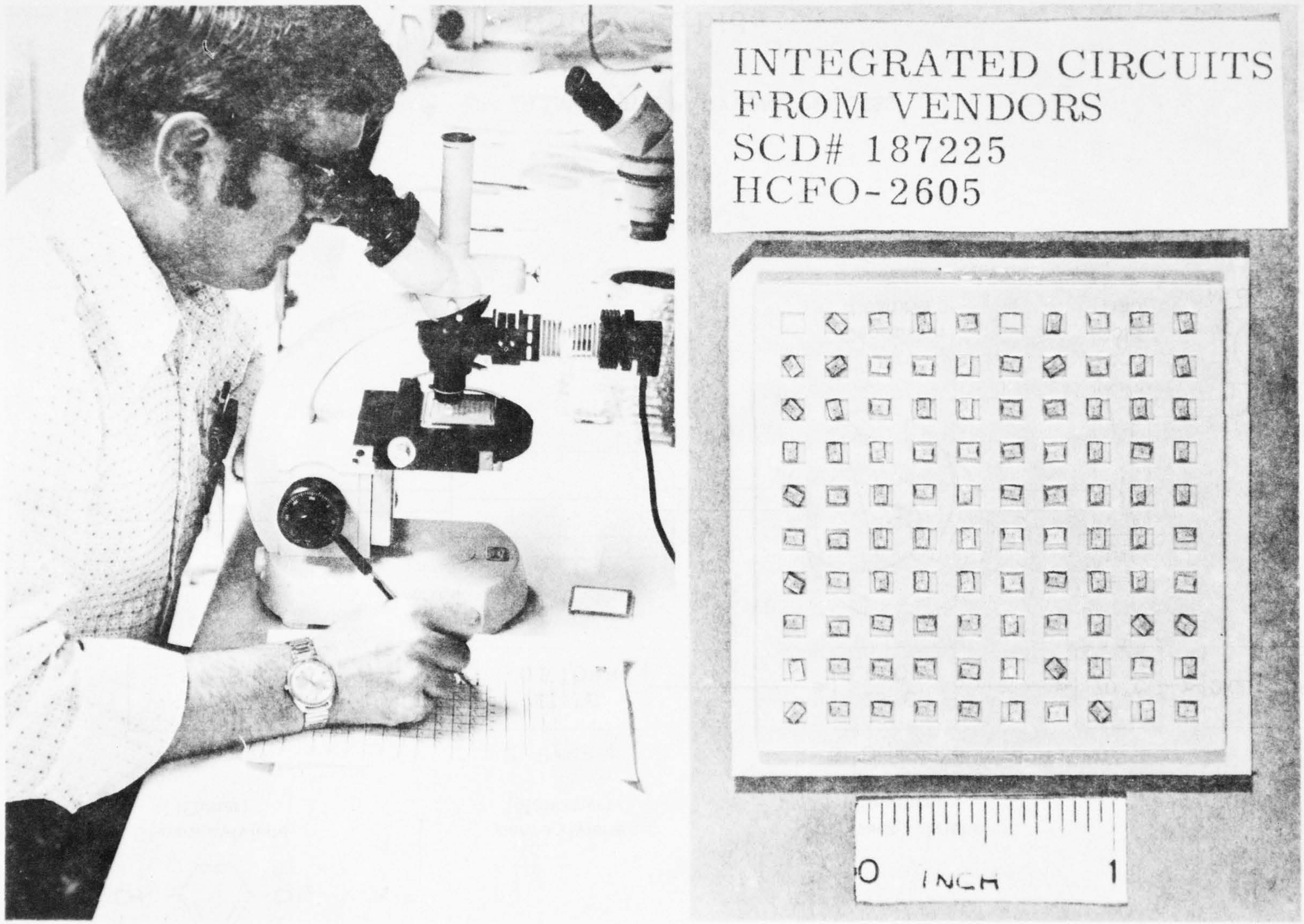
Figure 11



TYPICAL MODULE ASSEMBLY FLOW PLAN

FIGURE 12

The Charles Stark Draper Laboratory, Inc.



Rigid Inspection Criteria for Semiconductors

FIGURE 13

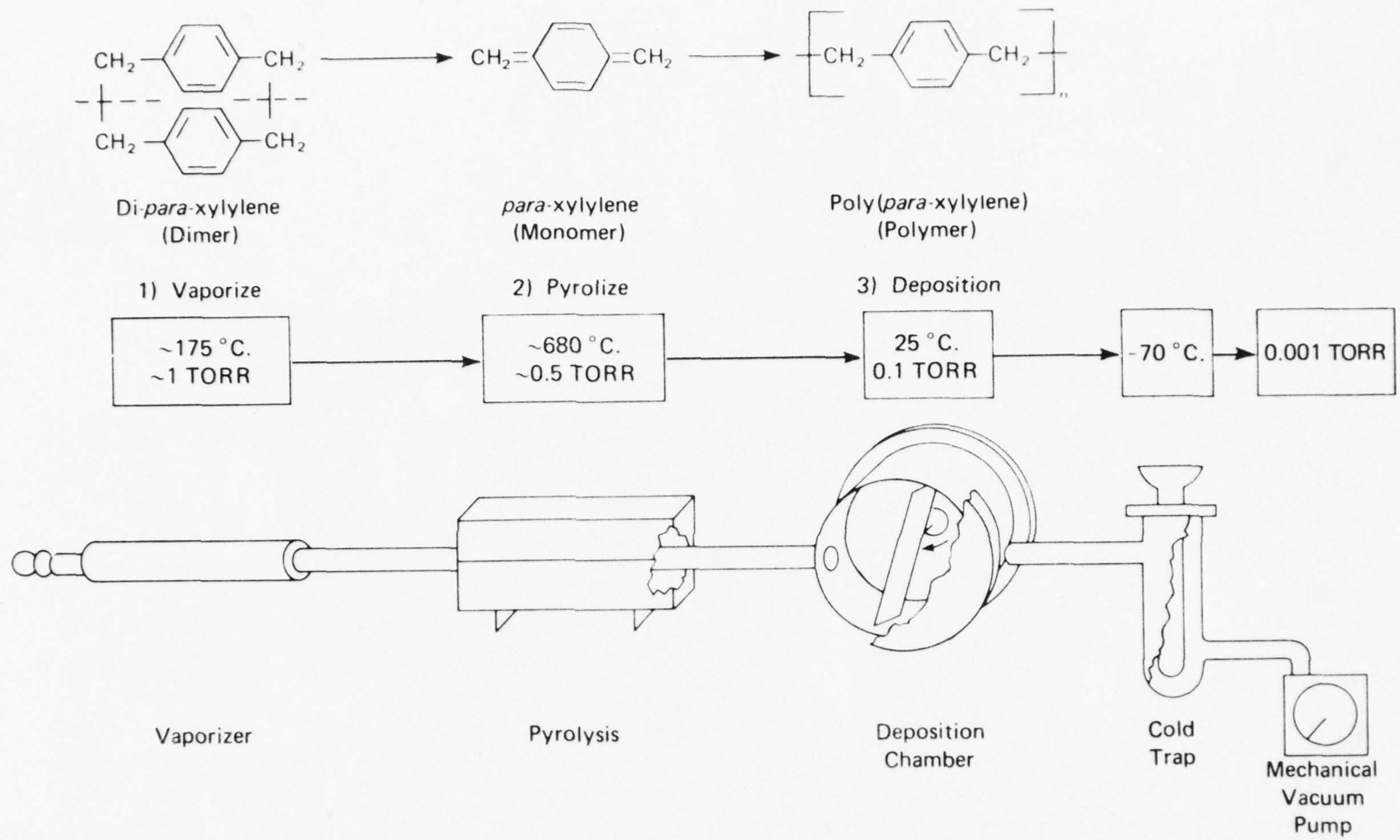
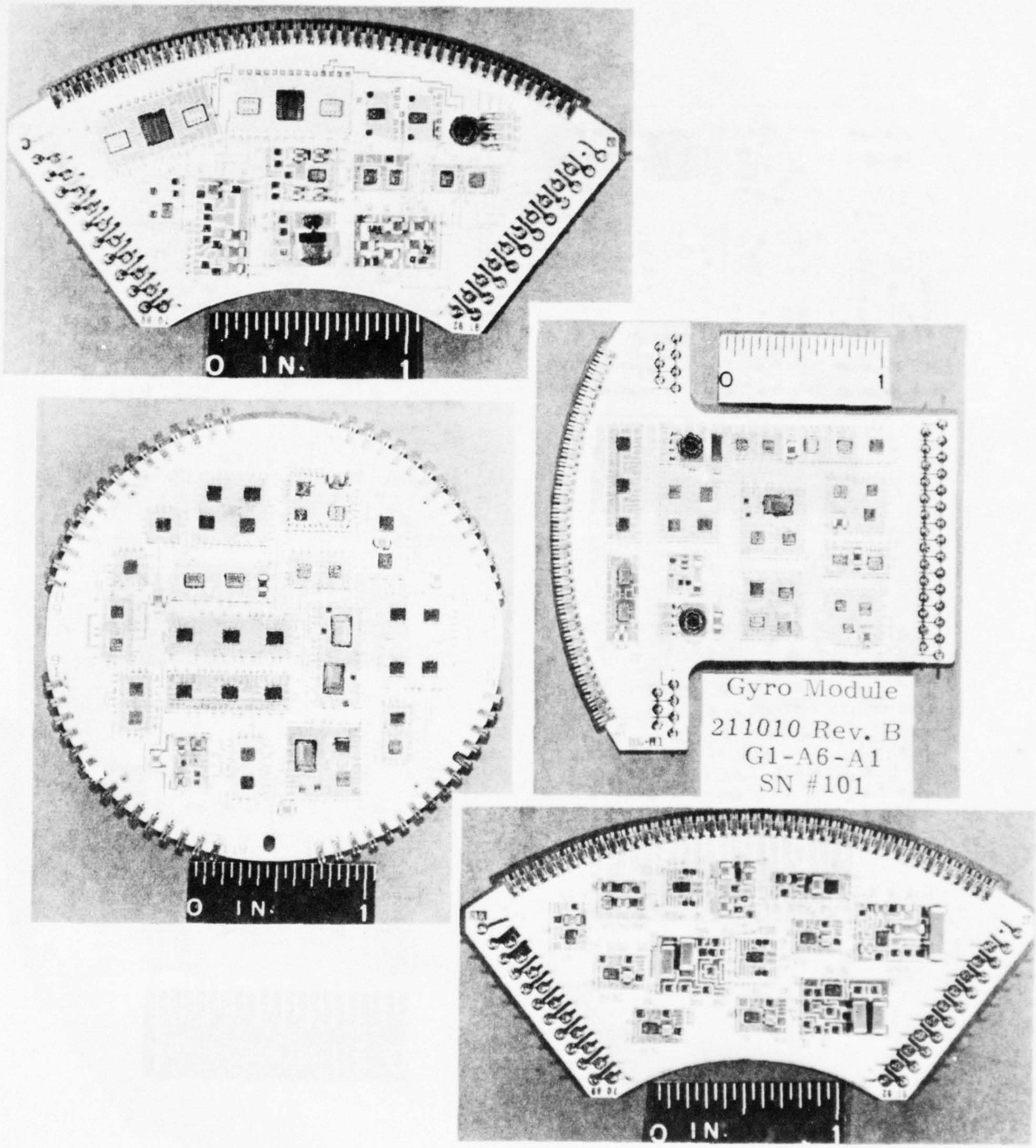


DIAGRAM OF THE PARYLENE PROCESS

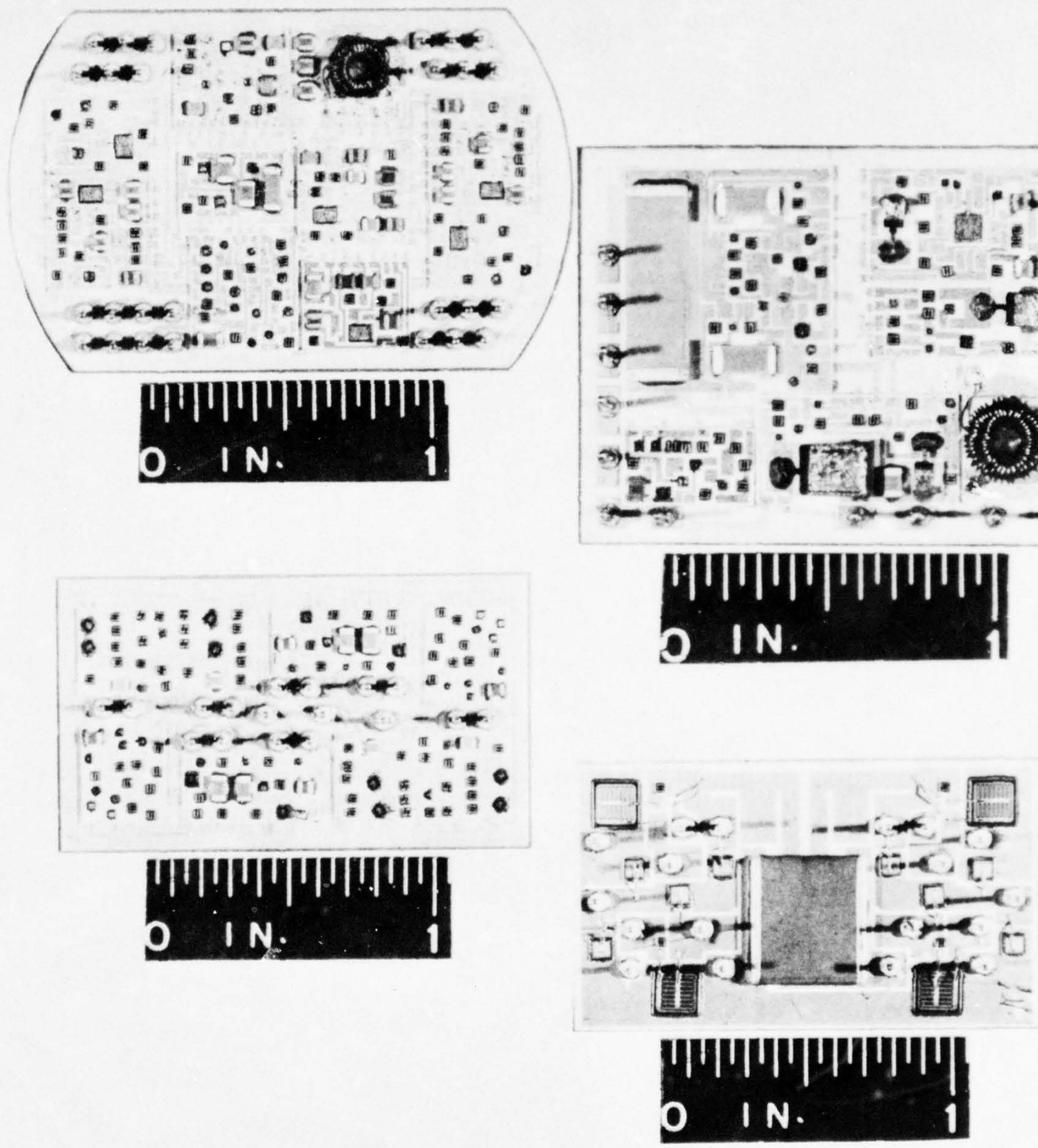
Union Carbide

FIGURE 14



Typical Examples of AIRS Hybrid Modules

FIGURE 15a



Typical Examples of AIRS Hybrid Modules

FIGURE 15b

The Charles Stark Draper Laboratory, Inc.

SUMMARY - AIRS ELECTRONIC ELEMENTS

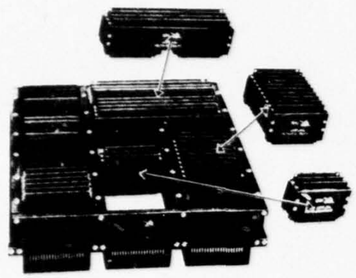
	UNIQUE	TOTAL
MODULES	81	150
CERAMIC MLB'S	62	102
THIN FILM MB	13	35
SUBUNITS	286	950
SUBUNIT ARTWORK	264	264
MODULE COVERS	33	139
SYSTEM MLB'S (EPOXY)	9	15
SYSTEM SINGLE LAYER BOARDS	5	12
SYSTEM FLEXTAPES	45	245
STRUCTURES	18	60

DEVICES (WITHOUT INSTRUMENTS)

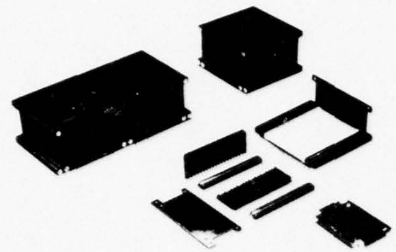
IC'S	847
TRANSISTORS / DIODES	1899
RESISTORS	3152
CAPACITORS	1633
TRANSFORMERS	125
TOTAL	7656

FIGURE 16

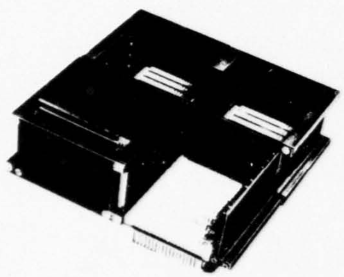
TYPICAL CAGES AND MODULES
using the IERC Standard Hardware Packaging System



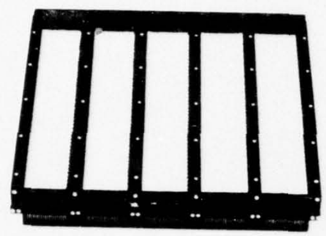
Level II Cages and Level I Alpha Series modules.



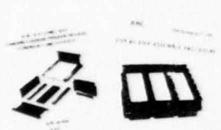
Level II Cage. Note the simple construction and single and double span modules in the same cage assembly.



Level II Cage. The IERC system is expandable in three directions: height, width and depth. RF shielding of the complete cage or individual sections can be provided.



Level II 5 span 50 cage, top view. There are 250 stations with a solid, back wiring panel.



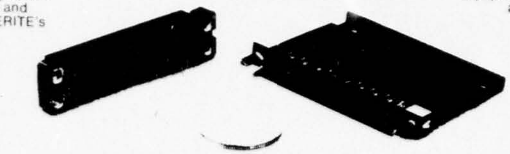
For your copies of these two informative booklets on the IERC SHP System call your local IERC representative or IERC.

Tooled originally to meet the requirements of the Navy's Standard Hardware Program, Masterite's (NAFI) module connector series has been broadened to include a line of connectors suitable for a range of commercial, industrial and military applications. Because of the adaptability of this connector style to any modular, building block design concept, be it a ship board fire control system or commercial television, a great selection of male/female combinations have been tooled and are available for general use. The purpose of this data sheet is to acquaint you with this connector style and demonstrate MASTERITE's scope of capability.

We invite you to advise us of your requirements or design problem. A connector may exist which will be suitable for your application; samples can be sent to you *immediately*. *If an existing connector* will not do the job, we will be pleased to propose a modification or new design.

CURRENT APPLICATIONS:

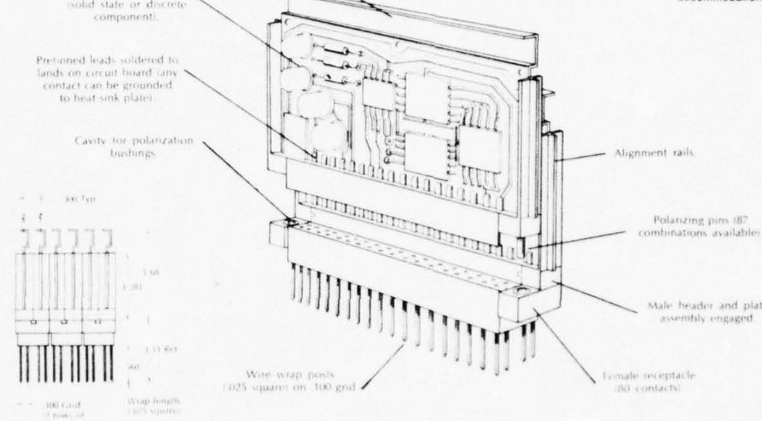
Telephone equipment, Communication terminals, Cash register, Electronic scales, Automotive test equipment, Television, and Ship board fire control equipment.



.050 and .100 Centers

The basic modular connector design consists of two 40 pin male headers and a female receptacle (80 contacts) which accommodates two male headers. A vertical aluminum plate, which is an integral part of each male header, acts as an engaging and disengaging handle and heat sink mounting surface for the user's circuit board modules (solid state or discrete components). Various plate styles are available including cut outs for component accommodation.

Male header and plate assembly disengaged



Examples of NAFI Structures

Figure 17

The Charles Stark Draper Laboratory, Inc.

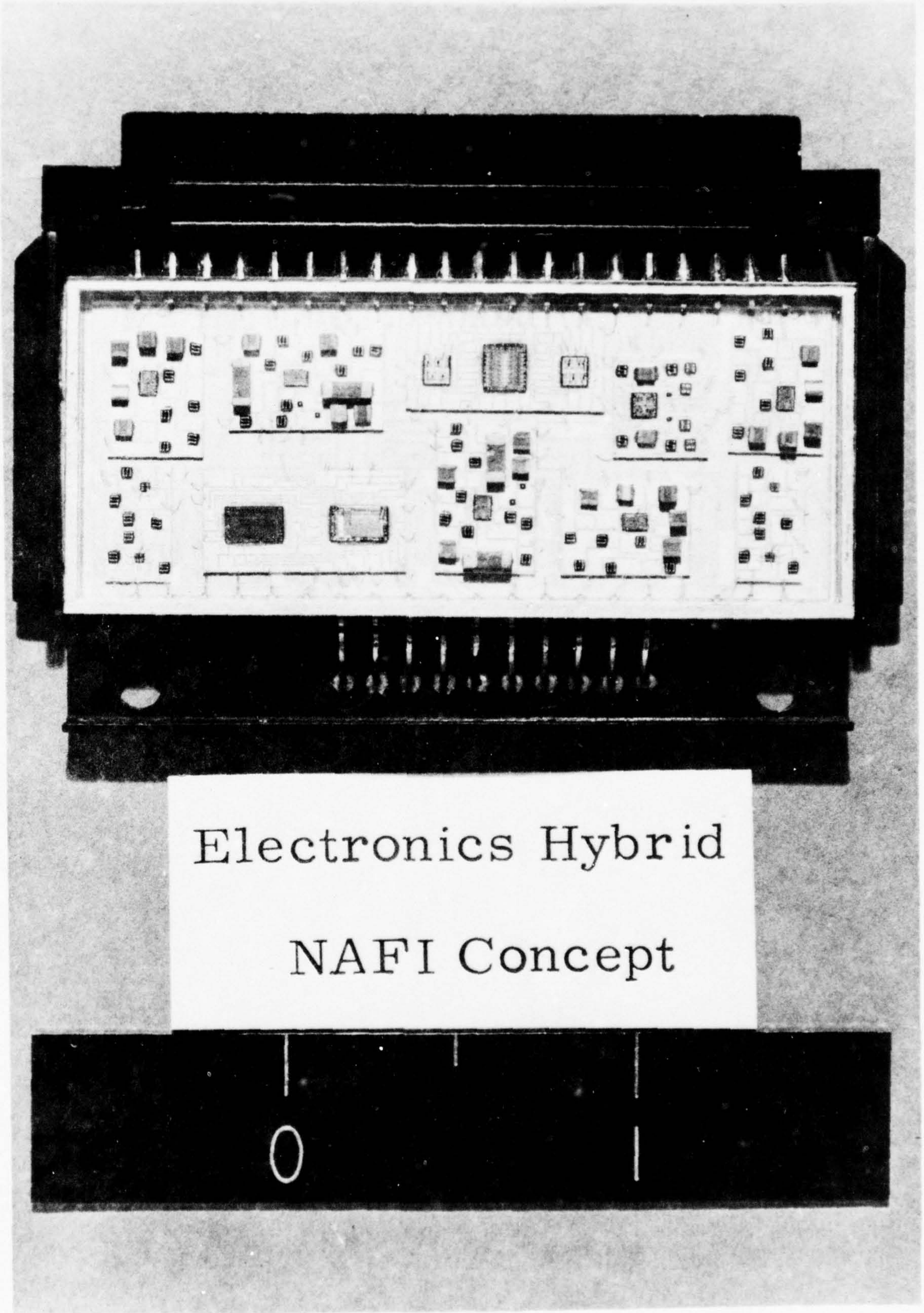


Figure 18

The Charles Stark Draper Laboratory, Inc.

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

PLANNING GROUP

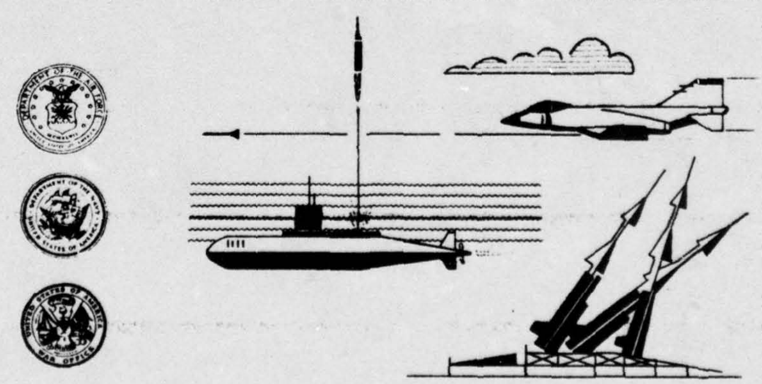
E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

SESSION II

TEST AND SUPPORT

NOV. 18 – 19 1975

**Joint Services
Data Exchange Group
for
Inertial Systems**



HOSTED BY

MACDILL AFB

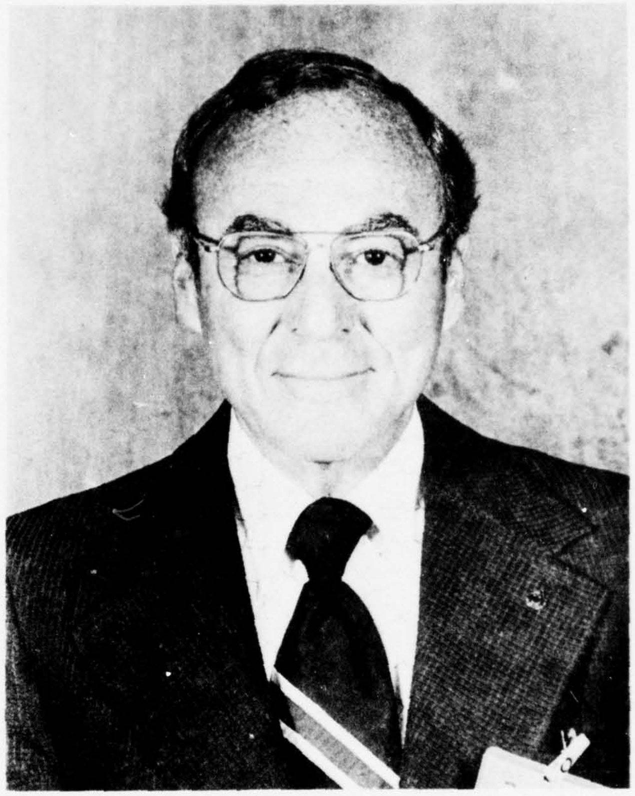
and

**HONEYWELL, AEROSPACE DIV.
ST. PETERSBURG FLA.**

SESSION II

TEST AND SUPPORT

SESSION CHAIRMAN



LEONARD R. SUGERMAN, COLONEL, USAF (RET)

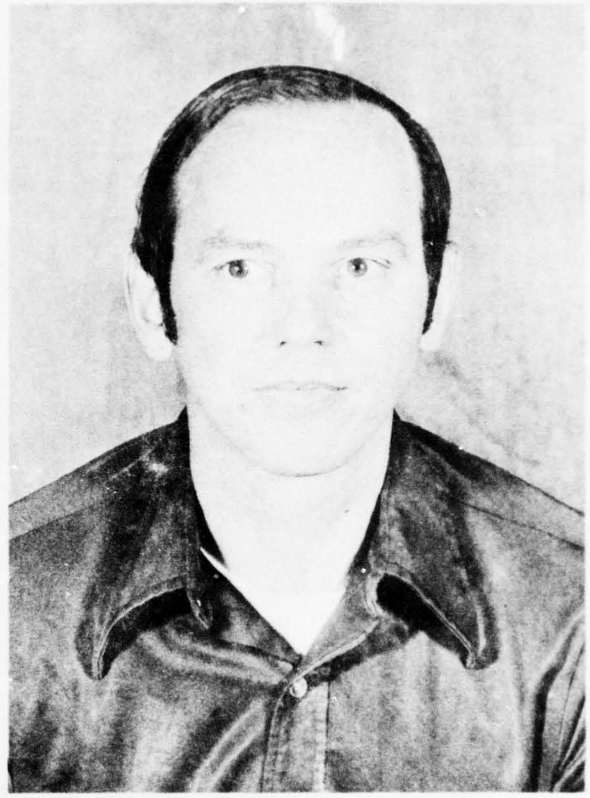
Now retired from the Air Force but still active in the inertial business, Len Sugerman was Chief of the Plans and Requirements Office, Air Force Special Weapons Center, Kirtland AFB, New Mexico. A past President of the Institute of Navigation he holds the Norman P. Hays Award and the Air Force Association Meritorious Award for management as well as his military decorations. He received his BS in Engineering from MIT and a Master's in Business Administration from the University of Chicago. He is the US Coordinator for the AGARD G&C Panel and is currently Consultant to the Physical Sciences Lab of the New Mexico State University.

BRIEFING TITLE

APPLICATION OF A MAINTENANCE WARRANTY APPROACH
IN THE SWEDISH AIR MATERIAL DEPARTMENT

JAN BROGREN

Mr. Brogren is employed by the Defense Material Administration, Air Material Department, Airborne Electronics Division, Stockholm, Sweden. He is head of the Flight Data Systems Group responsible for planning of avionic development and production phases for the Swedish Air Force. His Group prepares and analyzes system specifications, evaluates proposals and conducts negotiations with Swedish and foreign vendors. They are responsible for planning and layout of all levels of maintenance for air data computers and Inertial Navigation Systems and components. Mr. Brogren was his Country's Representative at Kearfott in the development of the INS for the JA 37 Viggen aircraft.



THEODORE "TED" CROSIER

Mr. Crosier received his Bachelor of Science Degree in Mechanical Engineering from the University of Akron and his Master of Arts Degree in Management and Supervision from Central Michigan University. He has been employed at AGMC since 1965. Prior to his current position as Chief of the Industrial Engineering Support Division, Plans and Programs Office, he was Manager of the Value Engineering Program.

APPLICATION OF A

RELIABILITY AND MAINTAINABILITY WARRANTY

Jan Brogren
Air Material Department
Stockholm, Sweden

Theodore E. Crosier
Newark Air Force Station
Newark, Ohio

Russell M. Genet
PRAM Office, WPAFB
Dayton, Ohio

Earl T. Bodem
Newark Air Force Station
Newark, Ohio

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

Clearwater, Florida

Nov 18-19 1975

AND

1976 ANNUAL RELIABILITY AND MAINTAINABILITY SYMPOSIUM

Las Vegas, Nevada

Jan 22, 1976

INTRODUCTION

This paper has been prepared in two parts. Part I explains how the Swedish Air Force is applying a reliability and maintainability warranty to an Inertial Navigation System. Part II explores the similarities between the Swedish warranty and the reliability improvement warranties being used in the United States Air Force.

PART I

APPLICATION OF A RELIABILITY AND MAINTAINABILITY WARRANTY IN THE SWEDISH AIR MATERIAL DEPARTMENT

With the procurement of the navigation system for the fighter version of the Viggen aircraft the Swedish Air Material Department entered for the first time the intricat world of Inertial Navigation. When consulting other countries Air Forces with inertial systems in their inventory, we learned that inertial systems are much more powerful than conventional attitude platforms, but extremely expensive to maintain.

Consequently a condition for us to get an approval by the government to go inertial was to be able to accurately estimate and control the maintenance costs.

Thus during the purchasing phase of the Inertial Navigation System, a special attention was paid to the reliability, maintainability and the life cycle cost of the equipments.

The cost of ownership became as an important evaluating factor as the performance and the initial cost of the equipment. We had to estimate the real field reliability with a high degree of confidence, and the time and cost for every main maintenance action.

To reach the highest possible confidence of the cost of ownership, we worked close with the maintenance analysis specialists at our Gyro System Central Depot which is called CVM. They participated and were also responsible for the parts of the contract which cover test and maintenance. At the same time the same specialists started their early planning work at the depot for the new equipment in the inventory.

To achieve a confidence high enough to compare the cost of ownership with the initial cost took us roughly one year of concentrated studies. The approach was a three stage analysis. At first we received from the different vendors all theoretical information regarding reliability and maintainability, but, as you know, those figures do not necessarily reflect the real life.

The second stage was to follow the test and repair actions performed at the vendors facilities in order to increase our knowledge about the maintainability of their equipment. Together with the respective vendor we selected some typical repair actions and followed and timed every single step of the repair from the incoming inspection to final delivery. We found that the time consumed and actions performed extensively exceeded the theoretical values submitted with the initial proposal.

I would like to comment, that inducing the vendors to perform this analysis was time-consuming, and difficult to negotiate. One vendor did not let us in his workshop and was consequently severly handicapped

in the competition.

The third stage was to analyze the data collected from the second stage and transfer it over to the overall maintenance approach of our depot. To make that possible we together with the vendor laid out preliminary maintenance flow diagrams showing not only time consumption for each operation but also preliminary specifications for test equipment and tools needed for the maintenance.

Finally we received sufficiently confident figures of our depot main - tenance cost over the life cycle of equipment. Now the big remaining question was how to put this into a covering guarantee clause in the contract.

The conventional Laboratory Reliability Demonstration and the Laboratory Mean Time to Repair Demonstration were not sufficient because we wanted the data to be representative of the actual operating environment, not the laboratory environment.

Some of the ideas that we finally worked out are close to what can be found in the avionics contracts for the commercial airlines.

The main and most important idea was holding the manufacturer responsible for the maintenance effort when performed at our repair facilities.

For that purpose he had to have detailed knowledge about the Swedish Air Force maintenance philosophies at all levels, how the central depot s orking, its organization, spare parts supply systems, etc.

We, therefore, made it possible for the different vendors maintenance specialists to visit and study our facilities in Sweden.

After the vendors had thorough knowledge of the depot and maintenance organization, they had to propose a Preliminary Maintenance Plan which was subject to several discussions between us regarding its content.

The plan was also agreed upon by the depot to be followed as a guideline for the maintenance layout.

The maintenance effort could not be expressed in Swedish crowns or US dollars due to different and unpredictable changes in currency and inflation for which the vendors could not be held responsible. The solution was to express the effort in time, in Maintenance Manhours, which divided by the Operating hours off the platforms (MMH/OH), became a measurement of our effort required to maintain the equipment.

The plan could now be used by the vendors as the ground material to calculate the MMH/OH.

At this point the vendors submitted quotes for the Inertial equipments, test equipments, tools, maintenance manuals, training courses, plus a guaranteed figure of the maximum maintenance manhours per operating hour.

Now I would like to give some information about the headlines of the guarantee clause.

The quantitative measurement of the guaranteed maintenance manhour per operating hour shall not begin until the 26th depot level repair action has taken place, avoiding the impact of the depot learning curve on the measurement.

The measurement of the guaranteed MMH/OH shall be in accordance with the Final Maintenance Plan to be agreed to by the parties. The plan will include definitions of Test Equipment, training, failure and repair specifications and procedures, repair manuals and record keeping.

Data from actual depot level maintenance activities shall serve as the basis for maintenance performance evaluation and shall as a minimum include time card records from all depot level maintenance actions, elapsed time indicator readings, spare parts requisition cards, test data, failure analysis and serial numbers of the equipments and major components being tested and maintained. This data shall be collected by and provided to the manufacturer by the depot.

Depot level repairs shall include failure localization, removal/ replacement of the defective component and verification of the repaired subunits and spare parts including acceptance testing and calibration where applicable in accordance with the mutually approved Final Maintenance Plan.

So called Maintenance Evaluation Meetings shall be instituted to be held every nine months, chaired by the Air Material Department with the manufacturer and depot personnel in attendance. The initial meeting will be held at the start of the measurement period with subsequent meetings to be held at nine month intervals thereafter. The prime purpose will be to evaluate the prior nine months maintenance data compiled by the depot, discuss the major problem areas and initiate corrective action recommendations as deemed necessary.

Initial accept-reject criteria for maintenance manhour per operating hour will be measured at the fourth meeting wherein the results over the past 27 months period will be established.

If this analysis reflects guarantee achievement, the manufacturer has fulfilled his contractual obligation.

In the event that this maintenance guarantee is not met, the manufacturer will be granted a nine months period to accomplish remedial actions. Remedial actions may include changes to the inertial equipment, test equipment, test procedures and maintenance practices.

Following the manufacturers demonstrated or initiated corrective action period, additional nine months audit periods shall be conducted for re-evaluation of the MMH/OH measurement critera. After demonstration of two consecutive nine months audit periods wherein the average MMH/OH

is equal to or less than the agreed upon level, the manufacturer shall be considered to have successfully completed this contract requirement.

In the event that this maintenance guarantee still is not met, the manufacturer, in addition to continuing to implement improvements, will undertake one of the following measures as directed by the customer:

a) Provide all Depot level Maintenance at his own expense.

b) Provide direct labor or equivalent cost reimbursement to the customer in the amounts required, to maintain the cumulative net actual labor effort consistent with the guaranteed MMH/OH, at no cost to the customer.

After long negotitations with the competing vendors Singer Kearfott was finally awarded the contract.

Kearfott has developed and delivered six prototype Inertial equipments to us. An option for switching over to the new Singer Kearfott 2600 platform was exercised early 1974, and three of those platforms have since then been delivered for use in our test aircrafts.

The decision of switching to the new platform was very much grounded on assumed improvements in better reliability and maintainability.

At the present time, however, in comparing, the reliability of the two generations of platforms, the new 2600 platform can not compete with the old KT70. The reason for this, I feel, falls with problems in program management, workmanship and quality control. I do not think it is inherent in the design itself.

To refine the preliminary maintenance plan and in detail define the logistic elements especially test equipment and spare parts furnishing our depot signed a one year Integrated Logistic Support contract with Kearfott.

During this year the depot and Kearfott people have been working together in Sweden and the United States.

The final report which is now delivered from Kearfott will form the base for the mutually binding Final Maintenance Plan.

As I previously said the idea of this warranty application is to hold the manufacture responsible not only for the reliability and maintainability of the equipment but also for the maximum maintenance effort when performed at the customers depot. I intend to within a few years report how successful we have been with this approach.

PART II

SIMILARITIES BETWEEN THE SWEDISH RELIABILITY AND MAINTAINABILITY WARRANTY AND THE UNITED STATES AIR FORCE RELIABILITY IMPROVEMENT WARRANTY

We at AGMC have been following Sweden's approach to warranty contracts for the past two years and will continue to do so in the future. We believe that you should be made aware of and take advantage of their experience. I would like to point out the similarities between the Swedish warranty and the Reliability Improvement Warranty (RIW) and raise this question.

Both the Swedish and US warranties have the same purpose, i. e., to accurately estimate and control life cycle costs (LCC) of INS.

Our objectives are identical. We are both seeking a contract that provides an incentive to the contractor for making reliability and maintainability improvements which reduce support costs. I can not stress enough that there are two equally important ways to reduce LCC; (1) keep it in the field longer, and (2) lower the repair cost.

The actual warranty contracts being used in Sweden and the US fix both contractor price and system performance while providing incentives for improved reliability and maintainability. Again, the desired end is reduced LCC, the emphasis being shifted from acquisition cost to total cost.

Both warranty approaches reduce government risk from the viewpoint that the contractor becomes responsible for reliability and maintainability improvements.

Both approaches overcome a real weakness in former INS reliability and maintainability testing and qualification. The benign environment of the laboratory and government test facilities is replaced with the actual operating and maintenance environment.

Greater emphasis is placed on LCC because those parameters that are the most sensitive in the LCC equation are given increased management attention. A real effort is made not only to control but to reduce cost.

Probably the most important benefit to the contractor is that he can compete in one contract for both production and support of INS. This increased responsibility naturally means larger potential contract dollars. His potential for profit is also increased with a fixed price contract. Readily attaining the contract reliability and maintainability requirements decreases his cost and benefits him financially.

The contractor gains something he never really had before. He has the influence to make recommendations for changes outside of the normal government approval cycles. He also has additional resources available for investigating and making changes, increasing his flexibility.

Since the contractor is now responsible for reliability and maintainability improvements, he now gains 'real world' R&M experience. He has complete knowledge about how his equipment is performing, being used and maintained. Heretofore this experience was piecemeal and in many cases gained in spite of and not because of contractual requirements.

The discussion to this point has covered those features and characteristics that are similar to the two approaches. I shall now explore some of the features offered by the Swedish approach and some of the RIW problems overcome by this approach.

The biggest plus found with the Swedish approach is that the government is no longer solely dependent on the contractors for support. This weakness no longer exists since government employees and facilities are utilized for maintenance. The risks of contractor strikes, bankruptcy and changes in management, etc. have been eliminated. The government has the absolute control required for war time surge and still has the contractor as a back up capability.

The Swedish approach does provide R&M incentives to the contractor plus maintainability incentives to the government depot.

Their approach requires R&M demonstration in the operating environment, a must for INS.

The Swedish approach has another unique feature. It is based on a contractor-government partnership. Instead of assuming that either party is all knowing, it recognizes the contributions of each. Who better knows the hardware than the contractor that designed and built it? Who better knows maintenance than the government depot that has specialized in this art? This team approach is essential for maximum utilization of both the contractor's and the depot's talents and experience. If such an approach were used in the United States - AGMC's 15 years experience in improving INS maintainability could be utilized and shared with the contractor.

Sweden's concept distributes the risk more equally. Instead of heaping it all on the contractor, the government gets into the act.

The depot becomes responsible for TAT and delivery guarantees.

The contractor's risk is reduced with the mutually developed maintenance plan. This plan increases the accuracy of maintainability and reliability predictions. Maintainability is completely defined and those factors affecting reliability controlled.

If problems do arise, the contractor is given time to evaluate data, recommend, validate and implement changes.

No R&M improvements are required if the contractor/depot are on the MMH/OH target from day one. No contractor effect would be required under this condition not even data collection. This is done for him by the depot.

The Swedish approach overcomes some of the RIW problems. It seems to offer a more simplified contract to both write and administer. The measurement of contractor effectiveness in terms of maintenance manhours per operating hours should help reduce the number of disputes related to unverified failures and relevant failures. The contractor and the government have really resolved their differences during the development of the maintenance plan. Again it reduces the dependence on the contractor, thus reducing support risk.

The real difference between the two approaches is that Sweden advocates a contractor/depot partnership while the RIW relies solely on the contractor. This need for increasing communication and cooperation is finally recognized contractually.

The Swedish approach accomplishes everything the RIW does and more. Their warranty decreases both contractor and government risk and takes advantage of government depot maintenance experience. This approach should be considered and compared to RIW. It should not be rejected out of hand.

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BRIEFING TITLE

REPORT ON AIR FORCE/NAVY CONTAMINATION SEMINAR

MIKE SAPUPPO

Mike Sapuppo is head of the Component Development Department of the Charles Stark Draper Laboratory, Inc. (formerly the Instrumentation Laboratory of MIT), and is responsible for the technical and administrative direction required to develop high-performance inertial components.

After receiving a BS Degree in Mechanical Engineering at MIT in 1952, he did research and development work on machine-cutting tools and fluids as an Army Ordnance Officer. He joined the Laboratory in 1954 and directed the design and development of the Pendulous Integrating Gyro Accelerometer (PIGA) and Pulsed Integrating Pendulum (PIP) series used in the Polaris, Minuteman, Apollo, Sabre, Poseidon, and Deep Submergence Inertial Navigation Systems. He also directed the development of advanced, highly-accurate sensors, Specific Force Integrating Receiver (SFIR), for the Electronics Research Center (NASA) and the Air Force (SAMSO).

He is a member of ASME, AIAA, and a registered professional engineer in Massachusetts.

REPORT ON AIR FORCE/NAVY CONTAMINATION SEMINAR

AN OVERVIEW

M. S. SAPUPPO

11/75 CD7686

OUTLINE

- INTRODUCTION
  - STATEMENT OF PROBLEM
  - PHILOSOPHY
    - CSDL/INDUSTRY
- CONTAMINATION CONFERENCES
  - HISTORICAL NOTES
    - REASONS FOR HAVING CONFERENCES
    - MEETINGS TO DATE
  - ASSESSMENT OF PROGRESS
- COMMENTS ON SPECIFIC PROBLEMS AND SOLUTIONS
- CLOSING REMARKS

11/75 CD7687

INTRODUCTION

- STATEMENT OF THE PROBLEM
  - CONTAMINATION AN INHERENT INGREDIENT IN EVERY PHASE OF LIFE: ANIMATE OR INANIMATE
  - LIFE AND PERFORMANCE
    - LARGE SCALE
    - MEDIUM LEVEL
    - LOWER (MACRO) LEVEL
    - LOWER (MICRO) LEVEL
- PHILOSOPHY – CSDL/INDUSTRY

CONTAMINATION IS AN INHERENT INGREDIENT IN EVERY PHASE OF LIFE, ANIMATE OR INANIMATE. CONTAMINANTS IN THE HUMAN BODY CAN CAUSE SICKNESS, DISEASE, AND DEATH. CONTAMINANTS IN FOOD CAN BE POISONOUS. CONTAMINANTS IN AIR LEAD TO POLLUTION. INGESTION OF CONTAMINANTS CAN ALTER HUMAN THOUGHT AND MODIFY HUMAN EMBRYONIC DEVELOPMENT DURING PREGNANCY. EXAMPLES OF THE DELETERIOUS EFFECT OF CONTAMINATION IN SPECIFIC INSTANCES ARE INNUMERABLE. LITTLE WONDER IS IT, THAT CONTAMINATION AFFECTS INERTIAL INSTRUMENTS AS WELL.

A FACET OF CONTAMINATION THAT BEARS ELABORATION IS THE CONCEPT OF QUANTITY OF CONTAMINATION AND ITS CONNECTION WITH DEGREE OF EFFECT. LARGE-SCALE CONTAMINATION CAN END LIFE IN AN ANIMATE BEING OR CAUSE CATASTROPHIC FAILURE IN AN INANIMATE INSTRUMENT IN A SHORT PERIOD OF TIME. LESSER CONTAMINATION CAN ALSO BUILD UP TO A HIGH LEVEL AND CAUSE SIMILAR RESULTS AFTER A LONG PERIOD OF TIME. LOWER CONTAMINATION LEVELS MAY BE TOLERABLE IN TERMS OF LIFE, WHILE CAUSING A DEGRADED LEVEL OF PERFORMANCE. STILL LOWER CONTAMINATION MAY NOT BE DETECTABLE AS AFFECTING LIFE OR PERFORMANCE, WITHOUT REALLY KNOWING WHETHER THE CONTAMINATION IS TRULY BENIGN OR SIMPLY PRODUCING AN EFFECT BELOW THE LEVEL OF PERFORMANCE BEING OBSERVED.

ALTHOUGH A DIRECT ONE-TO-ONE RELATIONSHIP BETWEEN LIFE AND PERFORMANCE FROM A CONTAMINATION EFFECT IS DIFFICULT TO ESTABLISH, SUCH A TREND APPEARS EVIDENT FROM EXPERIENCE. IN GENERAL, EXTENDED LIFE RELIABILITY IS DESIRED, WHEREAS PERFORMANCE IS USUALLY SPECIFIED AT REQUIRED LEVELS. AS A CONSEQUENCE, ACHIEVABLE HIGH PERFORMANCE HAS GENERALLY BEEN DEEMED UNNECESSARY WITHIN SPECIFIED LIMITS FOR A GIVEN APPLICATION. HOWEVER, THE CORRELATION BETWEEN LIFE AND PERFORMANCE INDICATES THAT THE COMPROMISE OF LOWER PERFORMANCE CARRIES WITH IT A COMPROMISE OF LOWER LIFE RELIABILITY.

CONTAMINATION IS AN UNWANTED, BUT REAL ASPECT OF HIGH-PERFORMANCE INERTIAL INSTRUMENTS. OUR PAST PHILOSOPHY CONCERNING CONTAMINATION HAS GENERALLY BEEN DEVELOPMENT OF PROCESS CONTROLS AIMED AT ELIMINATING CONTAMINATION AND THE NEED FOR FURTHER CONSIDERATION. IN REALITY, CONTAMINATION EFFECTS BECOME MINIMIZED AND STILL REQUIRE RESPECT AS AN INHERENT, UNAVOIDABLE PART OF INSTRUMENT DESIGN, FABRICATION, AND PERFORMANCE. THE PRESENCE OF CONTAMINATION SHOULD BE TRANSFORMED FROM A MALIGNANT CONDITION IN SOME UNITS TO A LOW-LEVEL BENIGN CONDITION IN ALL UNITS. IN OTHER WORDS, WE MUST ADMIT TO THE EXISTENCE OF CONTAMINATION IN OUR DEVICES AND OUR INABILITY TO TOTALLY ELIMINATE IT, AND ADOPT A PHILOSOPHY – WHICH PERMITS US TO ACQUIRE A TOTAL AWARENESS OF THE MANY ASPECTS OF CONTAMINATION CONTROL – ENABLING US TO UNDERSTAND ITS CHARACTERISTICS AND RAMIFICATIONS.

THE CHARLES STARK DRAPER LABORATORY

CONTAMINATION CONFERENCES

- HISTORICAL NOTES (DAVE GOLD/R. RYNEARSON)
  - REASONS FOR HAVING CONFERENCES
    - PROBLEM EXISTS INDUSTRY–WIDE
    - FORUM FOR INFORMATION EXCHANGE
  - MEETINGS TO DATE
    - 22–24 JANUARY 1975 – HONEYWELL, FLA
    - 8–9 OCTOBER 1975 – ROCKWELL INTERNATIONAL, ANAHEIM, CA
- ASSESSMENT OF PROGRESS TO DATE
  - RANGE OF SUBJECTS DISCUSSED
  - SOME TYPICAL/NOTEWORTHY CASES REPORTED

11/75 CD7689

AGENDA – WEDNESDAY, 22 JANUARY 1975

OPENING	S. ROHRBOUGH, HONEYWELL, FLA
WELCOME	R. RYNEARSON, HONEYWELL, FLA
CONTAMINATION CONTROL IN HIGH PERFORMANCE INERTIAL INSTRUMENTS – AN OVERVIEW	M. SAPUPPO, P. STERANKA C.S. DRAPER LABORATORY, INC.
CONTAMINATION CONTROL – A CASE HISTORY, PART I	J. CHASE, HONEYWELL, FLA
CONTAMINATION CONTROL – A CASE HISTORY, PART II	J. CHASE, HONEYWELL, FLA
BREAK	
G6B4 MINUTEMAN GYRO: A CASE HISTORY	M. JOHNSON, AUTONETICS DIV ROCKWELL INTERNATIONAL
TECHNIQUES FOR DETERMINING ATYPICAL GAS BEARINGS	J. HANKS, DRC
AN APOLLO ATTITUDE GYRO CASE HISTORY	P. JOHNSON, HONEYWELL, MINN

11/75 CD7692

THE CHARLES STARK DRAPER LABORATORY

AGENDA – THURSDAY, 23 JANUARY 1975

INSTRUMENT DESIGN ASPECTS OF CONTAMINATION MINIMIZATION	B. AHN, C.S. DRAPER LABORATORY, INC.
CONTAMINATION INDUCED FAILURES IN HYDRODYNAMIC CONICAL GAS BEARINGS	A. BUTLER, SINGER–KEARFOTT
BEARING CONTAMINATION CONTROL	R. SCHIESSER, C.S. DRAPER LABORATORY, INC.
BREAK	
TLC CONTAMINATION ANALYSIS OF GAS SPIN BEARINGS	R. McQUILLAN, NORTHROP
SOME EXPERIMENTS WITH CONTAMINATION INDUCED STORAGE POSITION ERRORS IN FLOATED INERTIAL INSTRUMENTS	J. ARONSON/P. STERANKA, C.S. DRAPER LABORATORY, INC.
SOURCES OF GASEOUS CONTAMINATION IN FLOATED INSTRUMENT DAMPING FLUIDS	W. CASTLEMAN, HONEYWELL, FLA
LUNCH	
PLASMA CLEANING TECHNIQUES	W. BALWANZ, NRL
WETTABILITY AS APPLIED IN THE BUILD OF GAS AND BALL BEARING GYRO MOTORS	S. KUMAR, SINGER–KEARFOTT
MAGNETIC MATERIAL REMOVAL FROM POTTING COMPOUNDS	D. GRZEGORCZYK, HONEYWELL, FLA
BREAK	
ULTRASONICS – THE EROSION EFFECT ON GYRO MATERIALS	H. YANCEY, B. BARTLETT, AUTONETICS DIV ROCKWELL INTERNATIONAL
SOLVENT REMOVAL OF SOLDER FLUX	F. OSWALT, SANDIA (AEC)
CLEAN WORK STATION AWARENESS TRAINING AT AUTONETICS	K. KENNEDY, AUTONETICS DIV ROCKWELL INTERNATIONAL

11/75 CD7693

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AGENDA – FRIDAY, 24 JANUARY 1975

MICROSCOPIC IDENTIFICATION OF CONTAMINANTS	W. McCRONE, McCRONE ASSOCIATES
ANALYTICAL METHODS FOR CONTAMINANTS	A. PASSCHIER, H. MOREEN, AUTONETICS DIV ROCKWELL INTERNATIONAL
MATERIAL SELECTION AS IT AFFECTS CONTAMINATION	J. STEMNISKI C.S. DRAPER LABORATORY, INC.
BREAK	
LOCATING AND DETECTING CONTAMINATION IN INERTIAL GUIDANCE AND OTHER AEROSPACE ELECTRO–MECHANICAL EQUIPMENTS	J. DeVORE, GEOS and J. PLENGE, GE ELECTRONICS
CONTAMINATION ANALYSIS USING VARIOUS ANALYTICAL TECHNIQUES	J. MUNARIN, L. DENTON, NAD NAVAL AMMUNITIONS DEPOT
INSTRUMENTATION TECHNIQUES IN CONTAMINANT DETECTION	J. MURDAY, L. JARVIS, NRL
LUNCH	
CONTAMINATION ANALYSIS BY MICROSCOPY	D. BROWN, HONEYWELL, FLA
VACUUM TECHNOLOGY AND CONTAMINATION ANALYSIS	R.RODRIGUEZ–TORRENT, HONEYWELL, FLA
MICROCONTAMINATION ANALYSIS BY IR AND OTHER SPECTROPHOTOMETRIC TECHNIQUES	S. WAGNER, HONEYWELL, FLA

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THE CHARLES STARK DRAPER LABORATORY

SEMINAR ATTENDEES – 22-24 JANUARY 1975
HONEYWELL, FLORIDA

NAME	COMPANY/AGENCY
JOHNSON, M.	AUTONETICS DIV ROCKWELL INTERNATIONAL
KENNEDY, D.	AUTONETICS DIV ROCKWELL INTERNATIONAL
PASSCHIER, A.	AUTONETICS DIV ROCKEWLL INERNATIONAL
YANCY, H.	AUTONETICS DIV ROCKWELL INTERNATIONAL
McLEOD, D.	AUTONETICS DIV ROCKWELL INTERNATIONAL
GOLD, D.	DEPT. OF NAVY (SSP) WASHINGTON, D.C.
WILSON, R.	DEPT. OF NAVY (SSP) WASHINGTON, D.C.
WEBER, A.	DEPT. OF NAVY (SSP) WASHINGTON, D.C.
PIRTLE, P., MAJ.	SAMSO/NORTON AFB
PEARSON, J., CAPT.	SAMSO/NORTON AFB
BOARDMAN, W., CAPT.	SAMSO/NORTON AFB
RYNEARSON, R.	HONEYWELL, FLA
BATES, D.	HONEYWELL, FLA
ORLANDO, V.	HONEYWELL, FLA
ROHRBOUGH, S.	HONEYWELL, FLA
ROSS, J.	HONEYWELL, FLA
HOLTZMAN, E.	HONEYWELL, FLA
BROWNE, D.	HONEYWELL, FLA
CASTLEMAN, B.	HONEYWELL, FLA
CHASE, J.	HONEYWELL, FLA
GRZEGORCZYK, D.	HONEYWELL, FLA
RODRIGUEZ– TORRENT, R.	HONEYWELL, FLA
WAGNER, S.	HONEYWELL, FLA
JOHNSON, P.	HONEYWELL, MINN

11/75 CD7691

THE CHARLES STARK DRAPER LABORATORY

SEMINAR ATTENDEES – 22-24 JANUARY 1975
HONEYWELL, FLORIDA

NAME	COMPANY/AGENCY	NAME	COMPANY/AGENCY
SAPUPPO, M.	C.S. DRAPER LAB	JACKSON, D.	LOCKHEED
LATTANZI, A.	C.S. DRAPER LAB	McCRONE, W.	W. McCRONE ASSOC. INC.
AHN, B.	C.S. DRAPER LAB	BUTLER, A.	SINGER–KEARFOTT
SCHIESSER, R.	C.S. DRAPER LAB	CABABE, H.	SINGER–KEARFOTT
ARONSON, J.	C.S. DRAPER LAB	KUMAR, S.	SINGER–KEARFOTT
DiPAOLA, R.	C.S. DRAPER LAB	WONG, S.	SINGER–KEARFOTT
LYNCH, A.	C.S. DRAPER LAB	HANKS, J.	DRC
MIOLA, J.	C.S. DRAPER LAB	FERGUSON, H.	DRC
SCHLUNTZ, R.	C.S. DRAPER LAB	KAZIN, S.	DRC
STEMNISKI, J.	C.S. DRAPER LAB	STAUFFER, R.	DRC
GOODMAN, H.	C.S. DRAPER LAB	RILEY, R.	TRW
FREEMAN, A.P.	C.S. DRAPER LAB	OSWALT, F.	SANDIA (AEC)
DENHARD, W.	C.S. DRAPER LAB	McQUILLAN, R.	NORTHROP
GARTNER, W.	C.S. DRAPER LAB	DAVIES, J.	NORTHROP
FAIRWEATHER, E.	C.S. DRAPER LAB	BALWANZ, W.	NRL
ROULE, R.	AEROSPACE CORP.	JARVIS, L.	NRL
DODGE, J.	AEROSPACE CORP.	MURDAY, J.	NRL
JONES, D.	AEROSPACE CORP.	WESTON, J.	NRL
KOPANIA, A.	AEROSPACE CORP.	SCHULIEN, H.	BENDIX CORP.
DEVORE, J.	GE, SYRACUSE, NY	MUNARIN, J.	NAD
MEEKS, R.	GE, ST.PETERSBURG	DENTON, R.	NAD
PLENGE, J.	GEOS	RAMSEY, J.	NAD
TANNER, E.	GEOS		

11/75 CD7690

THE CHARLES STARK DRAPER LABORATORY

AGENDA – WEDNESDAY, 8 OCTOBER 1975

8:30	ARRIVAL	
9:10	WELCOME	J.C. COZAD, EXECUTIVE VICE PRESIDENT, AUTONETICS GROUP
9:15	TESTING CAPABILITIES TO QUANTIFY CONTAMINATION EFFECTS	R.R. DiPAOLA, P. STERANKA, C.S. DRAPER LABORATORY, INC.
9:45	EVALUATION OF SURFACE CLEANLINESS BY SURFACE POTENTIALS	J.D. GUTTENPLAN, AUTONETICS GROUP
10:15	BREAK	
10:30	SURFACE COATINGS AS A SOURCE OF CONTAMINATION IN GAS BEARINGS	W. CASTLEMAN, HONEYWELL
11:00	PHILOSOPHY OF EFFECTIVE FAILURE ANALYSIS	R.H. JONES, AEROSPACE CORP.
11:30	INFORMAL DISCUSSIONS	
12:00	LUNCH	
1:30	MATERIALS & PROCESS CONTROL REQUIREMENTS FOR NON-VENTED GAS BEARING WHEEL ASSEMBLIES	R. WILLIAMS, F. STRACCIA, C.S. DRAPER LABORATORY, INC.
2:00	HIGH RESOLUTION PARTICULATE CONTAMINATION ANALYSIS	W.F. CONSTANT, AUTONETICS GROUP
2:30	OPTIMIZING INSTRUMENT FINAL CLEANING	A.G. GROSS, AUTONETICS GROUP
3:00	BREAK	
3:15	ANALYSIS OF CARBONACEOUS OVERLAYERS WITH SURFACE SENSITIVE SPECTROSCOPIES	N.L. JARVIS, J.S. MURDAY, NAVAL RESEARCH LABORATORY
3:45	FLEX CABLE CONNECTOR WELD FAILURES	E. TANNER, GENERAL ELECTRIC COMPANY
4:15	INFORMAL DISCUSSIONS	

11/75 CD7697

THE CHARLES STARK DRAPER LABORATORY

AGENDA – THURSDAY, 9 OCTOBER 1975

9:15	IN-SITU SEM ANALYSIS	H.A. MOREEN, AUTONETICS GROUP
9:45	DEMAGNETIZED RUNDOWN ANALYSIS TO INCREASE GAS BEARING RELIABILITY	E.M. GELOTTE, V.H. ASSARIAN, C.S. DRAPER LABORATORY, INC.
10:15	BREAK	
10:30	INFLUENCE OF EPOXIES ON GYRO GAS BEARING MOTOR CONTAMINATION	S. WONG, SINGER–KEARFOTT
11:00	DYNAMOMETER METHOD FOR DETERMINING THE PRESENCE OF CONTAMINATION IN A GAS SPIN BEARING	L.J. BLACHE, AUTONETICS GROUP
11:30	INFORMAL DISCUSSIONS	
12:00	LUNCH	
1:30	EXPERIMENTAL EVIDENCE FOR THE EXISTENCE OF TRAPPED POLAR COMPOUNDS WITHIN THE SURFACE OF AN INERTIAL QUALITY GYROSCOPE SHAFT	B.H. BAXTER, PRECISION PRODUCTS GROUP BRITISH AIRCRAFT CORP.
2:00	MICRO–CONTAMINATION ANALYSIS (A CASE HISTORY OF THE LEM LASER ALTIMETER)	R.A. McQUILLAN, NORTHROP CORP.
2:30	CONTAMINATION CAUSED ELECTRICAL NOISE ON SLIP RINGS	J.E. PLENGE, GENERAL ELECTRIC COMPANY
3:00	CONTAMINATION CONTROL ON FLIMBAL SYSTEM	H.A. GOODMAN, R. ROYLE, C.S. DRAPER LABORATORY, INC.
3:30	INFORMAL DISCUSSIONS	

11/75 CD7698

THE CHARLES STARK DRAPER LABORATORY

SEMINAR ATTENDEES – 8-9 OCTOBER 1975
ROCKWELL INTERNATIONAL, ANAHEIM, CA

NAME	COMPANY/AGENCY
CASTLEMAN, W.	HONEYWELL, INC.
ROHRBOUGH, S.F.	HONEYWELL, INC.
JONES, R.H.	AEROSPACE CORP.
WONG, S.	SINGER–KEARFOTT
DAVIES, J.H.	NORTHROP
McQUILLAN, R.A.	NORTHROP
BAXTER, B.H.	BRITISH AIRCRAFT CORP.
PLENGE, J.E.	GENERAL ELECTRIC
TANNER, E.G.	GENERAL ELECTRIC
HANKS, J.K.	DYNAMICS RESEARCH
GELOTTE, E.M.	C.S. DRAPER LAB
GOODMAN, H.A.	C.S. DRAPER LAB
SAPUPPO, M.S.	C.S. DRAPER LAB
SCHIESSER, R.J.	C.S. DRAPER LAB
STERANKA, P.	C.S. DRAPER LAB
WILLIAMS, R.L.	C.S. DRAPER LAB
LATTANZI, A.C.	C.S. DRAPER LAB

NAME	COMPANY/AGENCY
GUENTHNER, F.	SAMSO/NORTON AFB
JARVIS, N.L.	NAVAL RESEARCH LAB, WASHINGTON, D.C.
WEBER, A.	DEPT. OF NAVY WASHINGTON, D.C.
WILSON, R.E.	DEPT. OF NAVY WASHINGTON, D.C.
HELLER, H.E.	NAVY PLANT TECH REP. SSPO/ANAHEIM
WOLLENWEBER, C.E.	WALTER DARWIN TEAGUE ASS/SPA
KELLER, W.R.	AFPRO/QAE ROCKWELL INTERNATIONAL/ANAHEIM
SCOTT, D.R.	AFPRO ROCKWELL INTERNATIONAL/ANAHEIM
FRASER, R., Lt.	SAMSO/MNNG
GOO, R.	SAMSO/MNCPA
McVEY, W.A.	SAMSO/MNCPA
MARCHLENSKI, S.	AGMC/SNI, NEWARK AFS, NEWARK, OHIO
SWOPE, R.	AGE/MAGE, NEWARK AFS, NEWARK, OHIO

11/75 CD7695

THE CHARLES STARK DRAPER LABORATORY

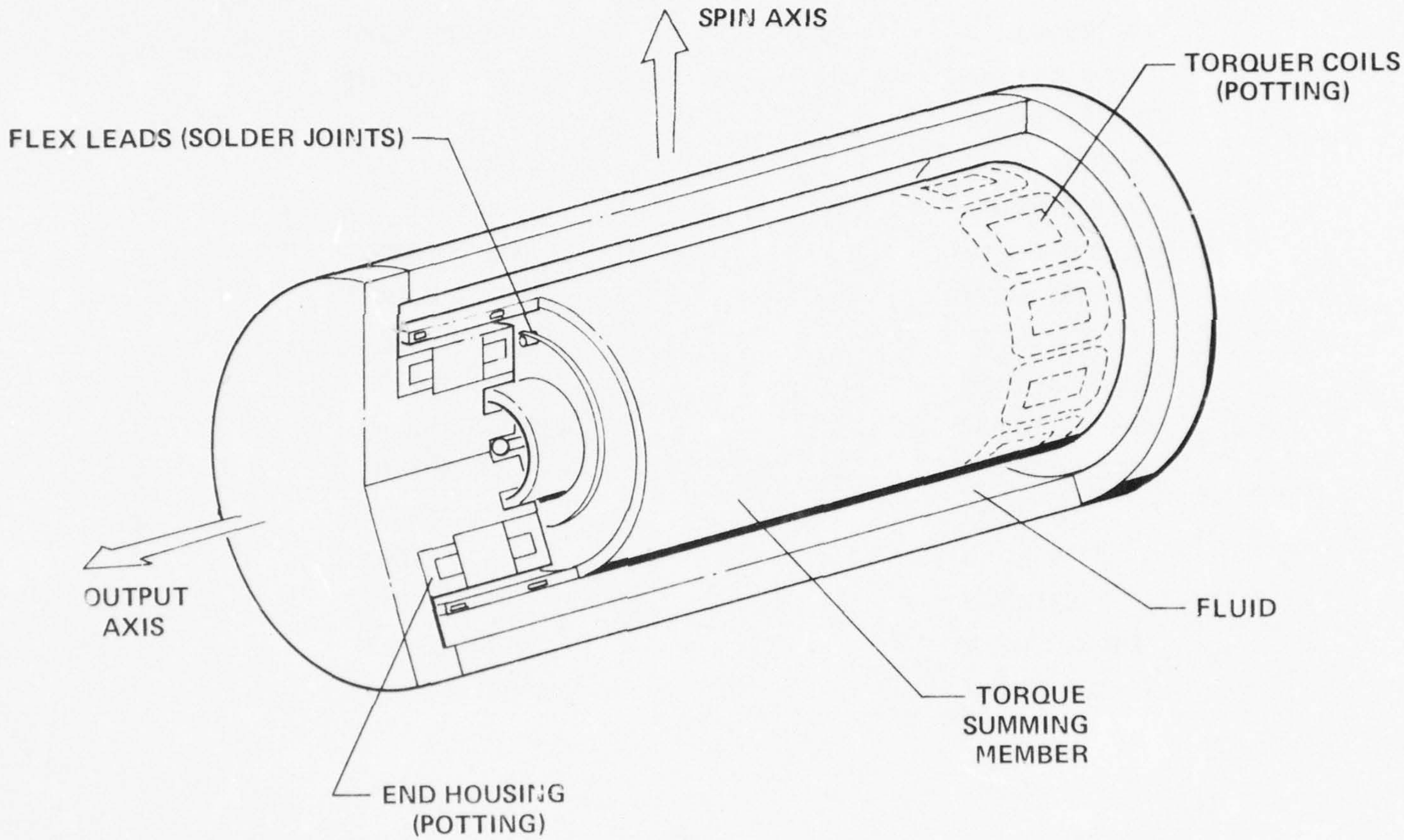
ROCKWELL INTERNATIONAL ATTENDEES

BARTLETT, B.C.
BERNSTEIN, A.L.
BLACHE, L.J.
BOEHM, R.C.
BOSSON, C.E.
CONSTANT, W.F.
DAVENPORT, M.L.
DILLBECK, J.A.
FARRAR, J.
GOW, K.P.
GRAHAM, R.F.
GROSS, A.G.
GUTTENPLAN, J.D.
HAGEN, G.R.
HARRIS, H.B.
JACKSON, R.L.
JAMES, G.G.
JOHNSON, M.T.
KALIHER, D.V.
LACY, M.E.
LUND, B.
McLEOD, D.L.
MIKOLEIT, F.B.
MITCHELL, R.E.
NELSON, G.N.
NOAR, R.
PASSCHIER, A.A.
PERKINS, A.A.
PERKINS, C.A.
TEBBETTS, R.H.
VALLES, A.G.
WHITBECK, R.A.

11/75 CD7696

THE CHARLES STARK DRAPER LABORATORY

FLOAT-LEVEL CONTAMINATION AREAS



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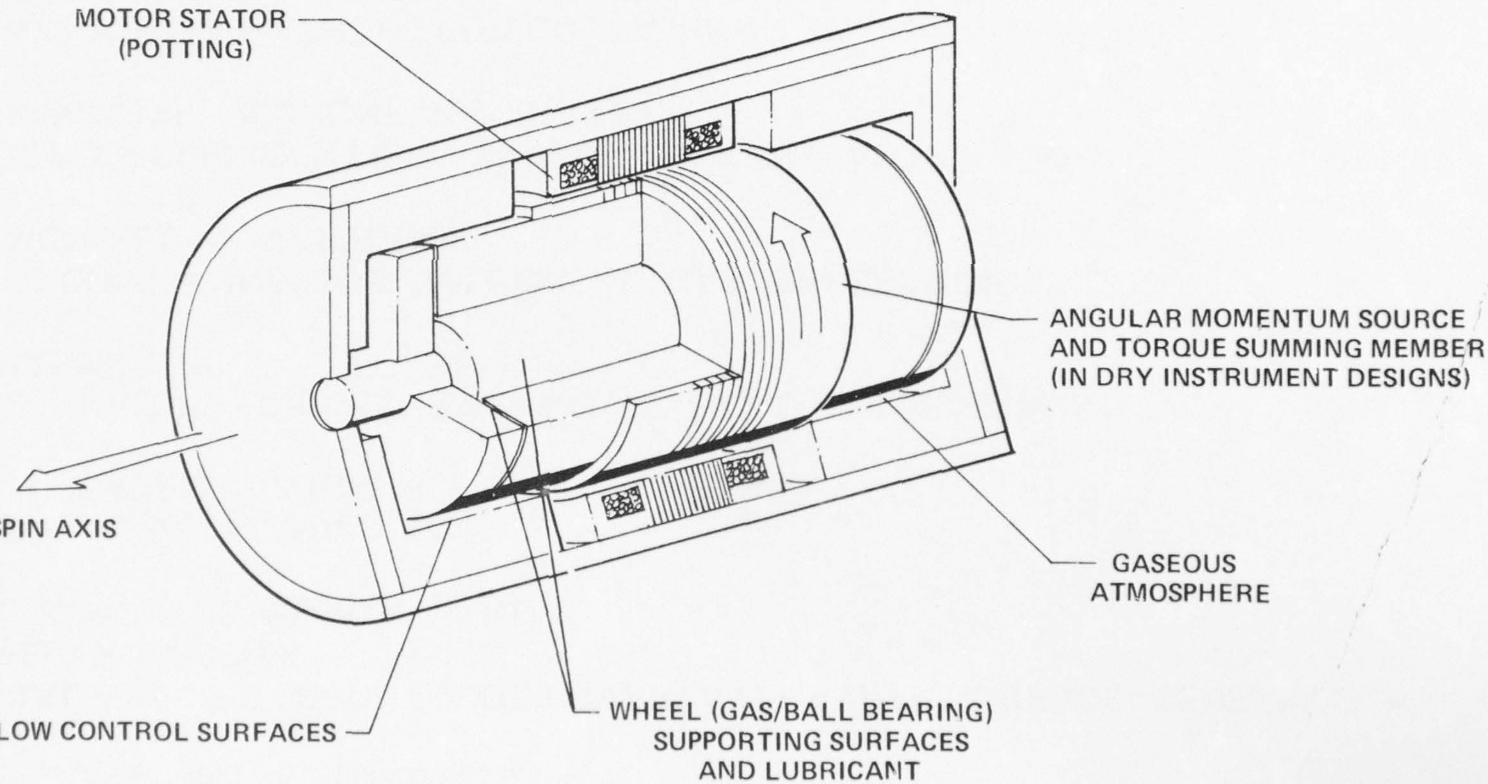
WHEEL-LEVEL CONTAMINATION AREAS



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AD-A031 049 AEROSPACE GUIDANCE AND METROLOGY CENTER NEWARK AIR FO--ETC F/G 17/7
DATA EXCHANGE FOR INERTIAL SYSTEMS (9TH), CONFERENCE PROCEEDING--ETC(U)
SEP 76 E T BODEM
UNCLASSIFIED AGMC-XRX-76-5 NL

3 OF 7
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ANALYSIS

"EVALUATION OF SURFACE CLEANLINESS BY SURFACE POTENTIALS"
J.D. GUTTENPLAN, AUTONETICS

"HIGH RESOLUTION PARTICULATE CONTAMINATION ANALYSIS"
W.F. CONSTANT, AUTONETICS

"ANALYSIS OF CARBONACEOUS OVERLAYERS WITH SURFACE–SENSITIVE SPECTROSCOPIES"
N.L. JARVIS/J.S. MURDAY, NRL

"IN–SITU S.E.M. ANALYSIS"
H.A. MOREEN, AUTONETICS

"TECHNIQUES FOR DETERMINING ATYPICAL GAS BEARINGS"
J. HANKS, DRC

"TLC CONTAMINATION ANALYSIS OF GAS SPIN BEARINGS"
R. MCQUILLAN, NORTHROP

"MICROSCOPIC IDENTIFICATION OF CONTAMINANTS"
W. MCCRONE, MCCRONE ASSOCIATES

"ANALYTICAL METHODS FOR CONTAMINANTS"
A. PASSCHIER/H. MOREEN, AUTONETICS

"CONTAMINATION ANALYSIS USING VARIOUS ANALYTICAL TECHNIQUES"
J. MUNARIN/L. DENTON, NAD CRANE

11/75 CD7701

ANALYSIS (continued)

"INSTRUMENTATION TECHNIQUES IN CONTAMINANT DETECTION"
J. MURDAY/L. JARVIS, NRL

"CONTAMINATION ANALYSIS BY MICROSCOPY"
D. BROWN, HONEYWELL

"VACUUM TECHNOLOGY AND CONTAMINATION ANALYSIS"
R. RODRIGUEZ–TORRENT, HONEYWELL

"MICROCONTAMINATION ANALYSIS BY IR AND OTHER SPECTROPHOMETRIC TECHNIQUES"
S. WAGNER, HONEYWELL

"ANALYTICAL APPROACH TO SURFACE ANALYSIS OR ALMOST EVERYTHING YOU WANTED TO KNOW ABOUT CONTAMINATION ANALYSIS BUT WERE AFRAID TO ASK"
J. STEMNISKI , CSDL

11/75 CD7702

PROCESS CONTROLS

"OPTIMIZING INSTRUMENT FINAL CLEANING"
A.G. GROSS, AUTONETICS

"BEARING CONTAMINATION CONTROL"
R.J. SCHIESSER, CSDL

"PLASMA CLEANING TECHNIQUES"
W. BALWANZ, NRL

"SOLVENT REMOVAL OF SOLDER FLUX"
F. OSWALT, SANDIA

"CLEAN WORK STATION AWARENESS TRAINING AT AUTONETICS"
D. KENNEDY, AUTONETICS

"CONTAMINATION INDUCED FAILURES IN HYDRODYNAMIC CONICAL BEARINGS"
A. BUTLER, SINGER–KEARFOTT

"MAGNETIC MATERIAL REMOVAL FROM POTTING COMPOUND"
D. GRZEGORCZYK, HONEYWELL

11/75 C 7704

MATERIALS

"SURFACE COATINGS AS A SOURCE OF CONTAMINATION IN GAS BEARINGS"
W. CASTLEMAN, HONEYWELL

"MATERIALS AND PROCESS CONTROL REQUIREMENTS FOR NONVENTED GAS–BEARING WHEEL ASSEMBLIES"
R. WILLIAMS AND F. STRACCIA, C.S. DRAPER LABORATORY, INC.

"INFLUENCE OF EPOXIES ON GYRO GAS–BEARING MOTOR CONTAMINATION"
S. WONG, SINGER–KEARFOTT

"EXPERIMENTAL EVIDENCE FOR THE EXISTENCE OF TRAPPED POLAR COMPOUNDS WITHIN THE SURFACE OF AN INERTIAL–QUALITY GYROSCOPE SHAFT"
B.H. BAXTER, PRECISION PRODUCTS GROUP, BRITISH AIRCRAFT CORP.

"INSTRUMENT DESIGN ASPECTS OF CONTAMINATION MINIMIZATION"
B. AHN, CSDL

"ULTRASONICS – THE EROSION EFFECT ON GYRO MATERIALS"
H. YANCEY/B. BARTLETT, AUTONETICS

"MATERIAL SELECTION AS IT AFFECTS CONTAMINATION"
J. STEMNISKI, CSDL

11/75 CD7703

TESTING

"TESTING CAPABILITIES TO QUANTIFY CONTAMINATION EFFECTS"
R.R. DIPAOLA/P. STERANKA, CSDL

"DEMAGNETIZED RUNDOWN ANALYSIS TO INCREASE GAS–BEARING RELIABILITY"
E.M. GELOTTE/V.H. ASSARIAN, CSDL

"DYNAMOMETER METHODS FOR DETERMINING THE PRESENCE OF CONTAMINATION IN A GAS–SPIN BEARING"
L.J. BLACHE, AUTONETICS

"SOME EXPERIMENTS WITH CONTAMINATION–INDUCED STORAGE POSITION ERRORS IN FLOATED INERTIAL INSTRUMENTS"
J. ARONSON/P. STERANKA, CSDL

11/75 CD7705

CASE HISTORIES

"PHILOSOPHY OF EFFECTIVE FAILURE ANALYSIS"
R.H. JONES, AEROSPACE

"FLEX CABLE CONNECTOR WELD FAILURES"
E. TANNER, GENERAL ELECTRIC COMPANY

"MICRO–CONTAMINATION ANALYSIS (A CASE HISTORY OF THE LEM LASER ALTIMETER)"
R.A. MCQUILLAN, NORTHROP

"CONTAMINATION–CAUSED ELECTRICAL NOISE ON SLIP RINGS"
J.E. PLENGE, GENERAL ELECTRIC COMPANY

"CONTAMINATION CONTROL ON FLIMBAL SYSTEM"
H.A. GOODMAN/R. ROYLE, CSDL

"CONTAMINATION CONTROL"
J. CHASE, HONEYWELL

11/75 CD7699

CASE HISTORIES (continued)

"G6B4 MINUTEMAN GYRO: A CASE HISTORY"
M. JOHNSON, AUTONETICS

"AN APOLLO ATTITUDE: GYRO CASE HISTORY"
P. JOHNSON, HONEYWELL

"CONTAMINATION CONTROL IN HIGH PERFORMANCE INERTIAL INSTRUMENTS"
M.S. SAPUPPO/P. STERANKA, CSDL

"LOCATING AND DETECTING CONTAMINATION IN INERTIAL GUIDANCE AND OTHER AEROSPACE ELECTRO–MECHANICAL EQUIPMENTS"
J. DEVORE, GEOS AND J. PLENGE, GE ELECTRONICS

11/75 CD7700

CLOSING REMARKS

NEXT CONFERENCE AT CSDL – NOVEMBER 1976

11/75 CD7706

BRIEFING TITLE

AIRCRAFT NAVIGATION TESTING AT THE CENTRAL INERTIAL GUIDANCE TEST FACILITY

PETER ZAGONE

Peter Zagone obtained his BS Degree in Electrical Engineering at the University of New Mexico, Albuquerque, NM, in June 1951. Since that time, he has been in the Research and Development Engineering Field on Missile Guidance and Control. For the last ten years, he has been Chief, Operational Test Branch, Central Inertial Guidance Test Facility, Holloman Air Force Base, New Mexico. In this capacity, he has been responsible for initiating, planning, and directing research and development test of guidance systems.

CAPT LARRY F. SANDLIN

Capt Larry F. Sandlin obtained his BS (1966) and MS (1968) Degrees in Electrical Engineering from the University of Kansas. From 1968 to 1972, he worked as a Project Officer for the Advanced Space Guidance Program at the Space and Missile Systems Organization, California. From 1973 to present, he has been a Test Director at the Central Inertial Guidance Test Facility, Holloman Air Force Base, New Mexico. He is Program Manager for the Aircraft Navigation System Verification Program, and has been Test Director for the Singer SKN-2400, Litton LN-37, Litton LTN-72 Verification Programs. Also, he was Test Director for the B-1 Navigation System, Autonetics N-57A (Micron Prototype) Inertial Navigation Test System, and the GEANS Navigation System Development Test Programs. His current programs include the Litton LN-40, Hamilton Standard HSDN-1010 and Singer SKN-3000.

AIRCRAFT NAVIGATION SYSTEM TESTING
AT THE CENTRAL INERTIAL GUIDANCE TEST FACILITY,
HOLLOMAN AIR FORCE BASE, NM

by

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FOREWORD

The 6585th Test Group's Central Inertial Guidance Test Facility (CIGTF) was established to provide a DOD capability to test and evaluate the products of the inertial navigation and guidance industry. The goals of the CIGTF are the following:

> Unbiased evaluation of components and systems, to provide data from which the customer can select the optimum equipment for a given mission application.
>
> Development of a single centralized test facility, to avoid the prohibitive costs of duplicated facilities.
>
> Standardization of tests, to provide common yardsticks for comparative evaluations.
>
> Competence in both personnel and equipment, to insure meaningful evaluation.

Originally established to provide test support for the development of early ballistic missile systems, the CIGTF has expanded its capability to cover the full spectrum of navigation and guidance equipment. The development of advanced precision test facilities and the acquisition of a hard core of experienced personnel have produced an unequaled facility for the evaluation of missile, spacecraft, and aircraft systems and components. This growing competence has resulted in increased emphasis on the role of the CIGTF as a national focal point for navigation system testing. The test facility is available to the three services, NASA, FAA, and private industry through government sponsorship.

The purpose of this paper is to briefly describe the unique capabilities and techniques available for aircraft navigation system testing that exist within the 6585th Test Group, Holloman AFB, New Mexico.

INTRODUCTION

The purpose of this paper is to describe the 6585th Test Group's Central Inertial Guidance Test Facility (CIGTF) aircraft navigation system test capabilities, the types of test programs conducted, and a review of recent tests accomplished at the CIGTF.

1. BACKGROUND

The United States Air Force, recognizing the need to centralize the considerable efforts and investments in manpower and equipment required for testing inertial guidance and navigation systems, established the "Central Inertial Guidance Test Facility" (CIGTF) in 1959. Located at Holloman Air Force Base in New Mexico, the CIGTF is in close proximity to the White Sands Missile Range, and thus can make use of the facilities of this well-known "best instrumented inland test range in the free world." The primary purpose of the CIGTF is to conduct the development testing of inertial components, systems, and complete navigation systems which are proposed for military applications.

Historically, the CIGTF grew and attained its status by testing inertial boost-phase guidance systems for Minuteman, Titan, Centaur, and Saturn. The emphasis has since shifted to evaluation of aircraft inertial navigation systems. The test methods and techniques for analytical evaluation of test results, which were rigoriously developed during the missile and space booster era, are applied to the validation of aircraft navigation systems.

The CIGTF began testing aircraft inertial navigation systems early in 1964. Relying upon a long history of extremely accurate results derived from sled testing, the analysts reasoned that comparable results could be obtained if testbed aircraft were continuously tracked by radar. Because the FPS-16 radars on WSMR can accomplish this to an accuracy of less than one hundred feet, a new era in precision evaluation was entered.

The first test of CIGTF capacity and capability was the Mark II Avionics competition. Six navigation systems were tested in this program between May and September 1965. Final report on the Mark II tests was delivered by November 1965. The success of this program led to a DDR&E Directive designating the CIGTF, Holloman AFB, as the DOD focal point for aircraft inertial navigation test evaluation.

The first Test Program document was originally published in March 1966 to aid in implementation of Dr. Brown's memorandum concerning test and evaluation of aircraft inertial navigation systems. In April 1967, Dr. Foster reiterated the need for a central test agency, quoted here in part:

> "...An Aircraft Inertial Navigator Test and Evaluation Program is established at the Central Inertial Guidance Test Facility (CIGTF), Holloman Air Force Base, which is the DOD focal point for aircraft inertial navigator test and evaluation. This CIGTF program will verify the expected performance of inertial navigators and will provide comparative results under the same test conditions. Through this process, avionics developers and/or Contract Definition (formerly PDP) contractors will have a number of inertial navigators to choose from whose performance has been verified, thereby minimizing the risks to the Government in their selection...."

The standardized tests to be described in this paper were established to fulfill the intent of the DDR&E Directive referred to above, and provide a realistic basis for comparative analysis of systems or components prior to their selection for any specific DOD application. The resulting data enables the Air Force to select the best available equipment for either future weapon system development or modification of existing systems.

2. ORGANIZATION

The 6585th Test Group's Central Inertial Guidance Test Facility (CIGTF), with the support of other Test Group agencies and several test ranges, provides the capability for complete test and performance evaluation of inertial navigation systems. This permits unbiased performance evaluation under conditions closely simulating an operational environment at a cost less than contractor testing.

The CIGTF manages the overall program during these tests. In addition to identifying resource requirements and preparing test plans and program documentation, the CIGTF performs laboratory tests, maintains all instrumentation support equipment, including the Completely Integrated Reference Instrumentation System (CIRIS), analyzes the test data, and prepares engineering and analysis reports.

The 6585th Test Group's Aeronautical Test Division maintains and modifies the aircraft palletized testbeds on which test systems are flown, and is responsible for the operational conduct of the flight test.

3. TYPES OF TESTS

Flight test programs are divided into two categories: Developmental programs and verification programs. Developmental tests of early prototype equipment provides information for design improvement and performance evaluation. Verification tests are performed on systems which are well along in the development cycle, and which have normally undergone some previous dynamic testing. This paper discusses primarily system verification tests; however, many of the concepts apply equally to developmental tests.

The types of system navigation mechanizations which are tested include pure (unaided) inertial, doppler heading reference, conventional doppler-inertial, Kalman doppler-inertial, loran-inertial, doppler-inertial-loran, and stellar-inertial-doppler. Systems may employ different alignment schemes including ground, air, and transfer of alignment. A basic verification test program is outlined in Table I.

The types of testbed aircraft currently in use for verification flight tests are C-141 transport, the RF-4C fighter, and an Army (UH-1H) helicopter. A limited amount of ground testing is done for every verification program, and van testing is available.

4. TEST OBJECTIVES

The principal goal of a verification program is to provide a fair, impartial, and rigorous system evaluation under standardized conditions. The program determines the navigation performance and operational suitability of the navigation system through a series of ground and flight tests. The standardized test conditions correspond as closely as possible to those expected operationally. Strengths and weaknesses of the systems are identified. Other government agencies may use this information to compare systems of the same type, and to choose the best system for new avionics applications.

5. TEST APPROACH

The basic verification program for an inertial navigation system is outlined in Table I. It consists of four phases: pre-delivery, ground, transport, and intended mission application test phases. Each system must advance through each of these phases in the above order. Systems intended for several potential applications may require testing in all three aircraft testbeds.

TABLE I

PHASE		WEEKS	FLIGHTS
0	Predelivery Ground Tests	(1 day)	0
2	Static Nav Tests		
I-A	Standard Ground Tests	2-4	(7-9 tests)
1-3	Functional Checkout Tests		
2	Static NAV Tests		
3	Scorsby Tests		
1	Heading Sensitivity Tests		
I-B	Special Ground Tests	0-2	(0-6 tests)
0-3	Special Analysis Tests		
0-3	Special Application Tests		
II	NC-141A Cargo Flight Tests	8-12	17-22
1-2	Functional Checkout Flights		
6	West 84 Min Cruise Profile and Return		
6	North 84 Min Cruise Profile and Return		
3	East 84 Min Cruise Profile and Return		
1-2	Terminate at a Distant Point/RON/& Return		
0-3	Special Analysis		
III-A	UH-1H Helicopter Flight Tests	8-10	19-26
1-2	Functional Checkout Flights		
6	East 42 Min Cruise Profiles and Return		
6	North 42 Min Cruise Profiles and Return		
6	East Terrain Mapping Missions		
0-6	Special Analysis Flights		
III-B	RF-4C Fighter Flight Tests	8-12	21-24
1-2	Functional Checkout Flights		
6	West 42 Min Cruise Profiles and Return		
6	West 42 Min Cruise/Simulate Ordnance Delivery Profiles and Return		
6	West 42 Min Cruise/Simulate Air Combat Maneuvers and Return		
2-4	Special Analysis Flights		
III-C	Extended NC-141 Cargo Flight Tests	4-8	5-11
0-1	Functional Checkout Flights		
2-3	West/NW 168 Min Cruise Profiles and Return		
2-3	East 168 Min Cruise Profiles and Return		
1	East/SE/terminate at distant point/RON/ and Return		
0-3	Special Analysis Flights		

RON - Remain Over Night

The basic program outlined in Table I is the minimum required to verify the primary alignment and navigation mode of the inertial navigation system. The objective of the verification is to establish a level of statistical confidence in the performance of the system for its primary operating mode in a typical operational environment. Many systems will have more than a single alignment and navigation mode. In addition, a system may be intended for a unique operational flight profile which is not adequately considered in the basic test program. Consequently, a test program will frequently include additional flights beyond the requirements of Table I.

A fair and valid verification test program is conducted by adhering to the following strict test discipline. The system is operated and tested solely by Air Force personnel. Also, Air Force personnel will determine the validity and usability of test data, and resolve all day-to-day operational test problems. This includes all test scheduling and declaring whether the system is ready for test or out for maintenance. All necessary maintenance and repair of the system and its support equipment is controlled by Air Force personnel.

A complete record is kept of pertinent data, such as system operating time, reaction times, system maintenance, and any special modifications to system configuration. Detailed operating and checkout procedures and test schedules are established prior to each test.

6. VERIFICATION TEST PHASES

a. Pre-Delivery Ground Test (Phase 0)

The purpose of this test is to obtain a confidence that the system to be delivered to Holloman Air Force Base will function within the limits required. This test is designed as a functional check to be performed at the Contractor's facility, witnessed by Air Force personnel, prior to delivery to Holloman Air Force Base.

b. Standard Ground Test Series (Phase I)

(1) The purpose of Phase I is to insure that the test system is in a satisfactory operational condition after shipment to Holloman Air Force Base and prior to entering the cargo flight test phase. During this phase, initial system and instrumentation equipment installation are accomplished on the selected C-141 testbed pallet, and appropriate Class II modification documentation is started.

(2) For laboratory evaluation of system accuracy during Phase I, the system will normally be operated for two 6-hour static navigation runs and three 6-hour Scorsby runs (see Figure 1). These runs will be performed with the system at nominal ambient temperatures. If necessary, platform cool down between tests can be accelerated with refrigerated air. The Scorsby rate will be six cycles per minute at $\pm$ 3° amplitude (6° peak-to-peak swing). During one of the static tests and one of the Scorsby tests, the system will be rotated to the four cardinal headings at intervals of 84 minutes. During the Scorsby tests, the table amplitude will be gradually reduced to zero prior to turning the system to a new heading, and then gradually increased back to $\pm$ 3°. Turning rate will approximate an aircraft turn rate of about 180 degrees/minute.

(3) The heading sensitivity test described in the paragraph above will be complemented by a second form of heading sensitivity test for comparison purposes. This test will consist of 84-minute static runs at each of the four cardinal headings, with each cardinal run being preceded by a 20-minute realignment with the platform pointed northward. The initial alignment will follow a warmup period sufficient to preclude the effects of temperature transients.

c. Cargo Test (Phase II)

(1) Table I outlines the number of tests to be conducted during Phase II. The number of valid data flights required is a function of system configuration and operating modes, normally requiring from 17 to 22 flights.

(2) In Phase II the system's navigation performance is tested on different headings. Some missions consist of North-South profiles; others will be East-West profiles. The number of turns are minimized though altitudes and air speeds may vary. Missions will usually be out and back profiles, although at least two will terminate at locations over 500 miles distance from the takeoff point.

(3) Many systems will have more than a single alignment and navigation mode. In addition, a system may be intended for a unique operational flight profile which is not adequately considered in the basic test program. Consequently, the test program will sometimes include additional flights beyond the requirements of Table I. If the system has a potential application as a long duration navigator, it will undergo extended cargo testing (Phase III-C) prior to advancing to helicopter or fighter test phases.

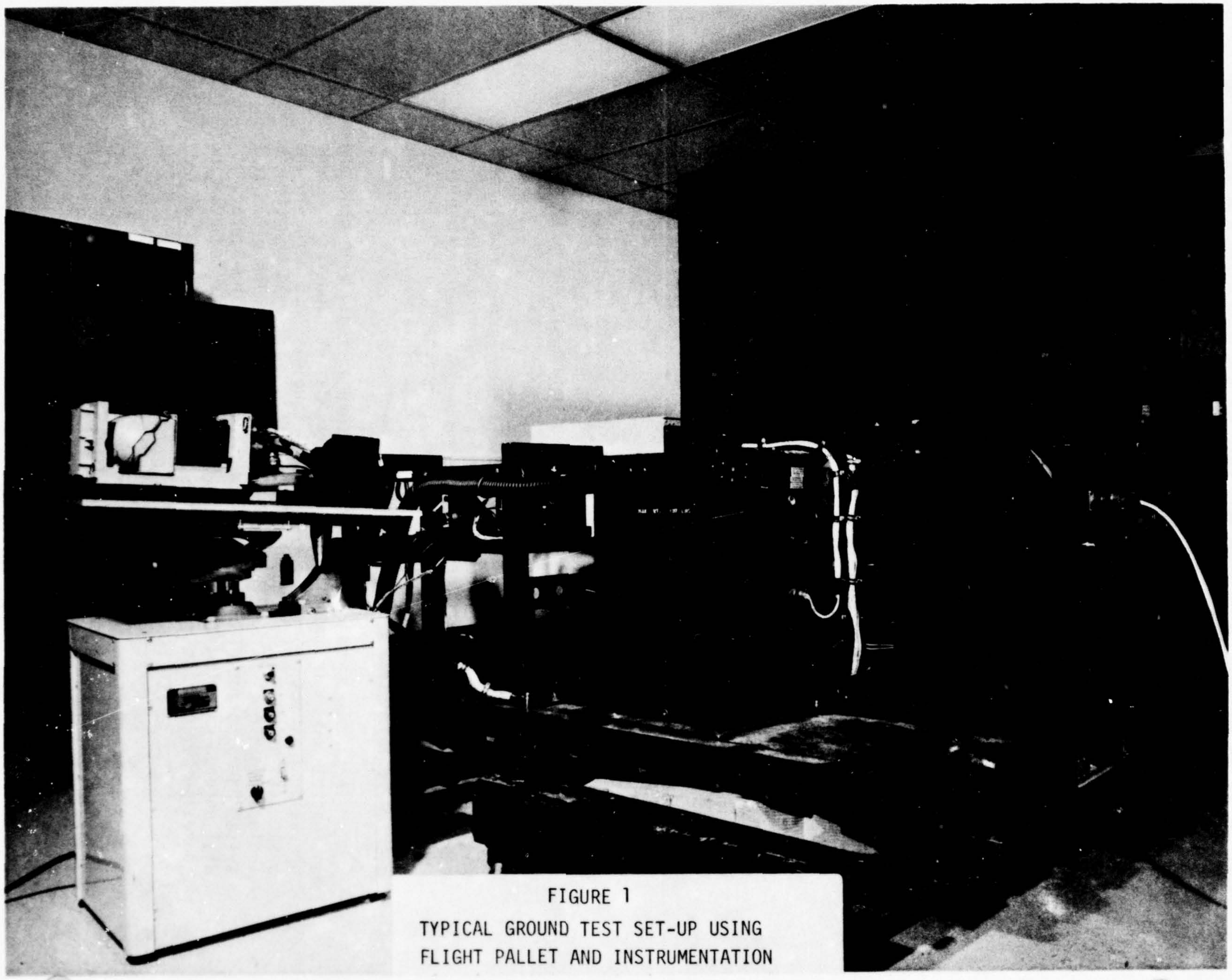


FIGURE 1

TYPICAL GROUND TEST SET-UP USING
FLIGHT PALLET AND INSTRUMENTATION

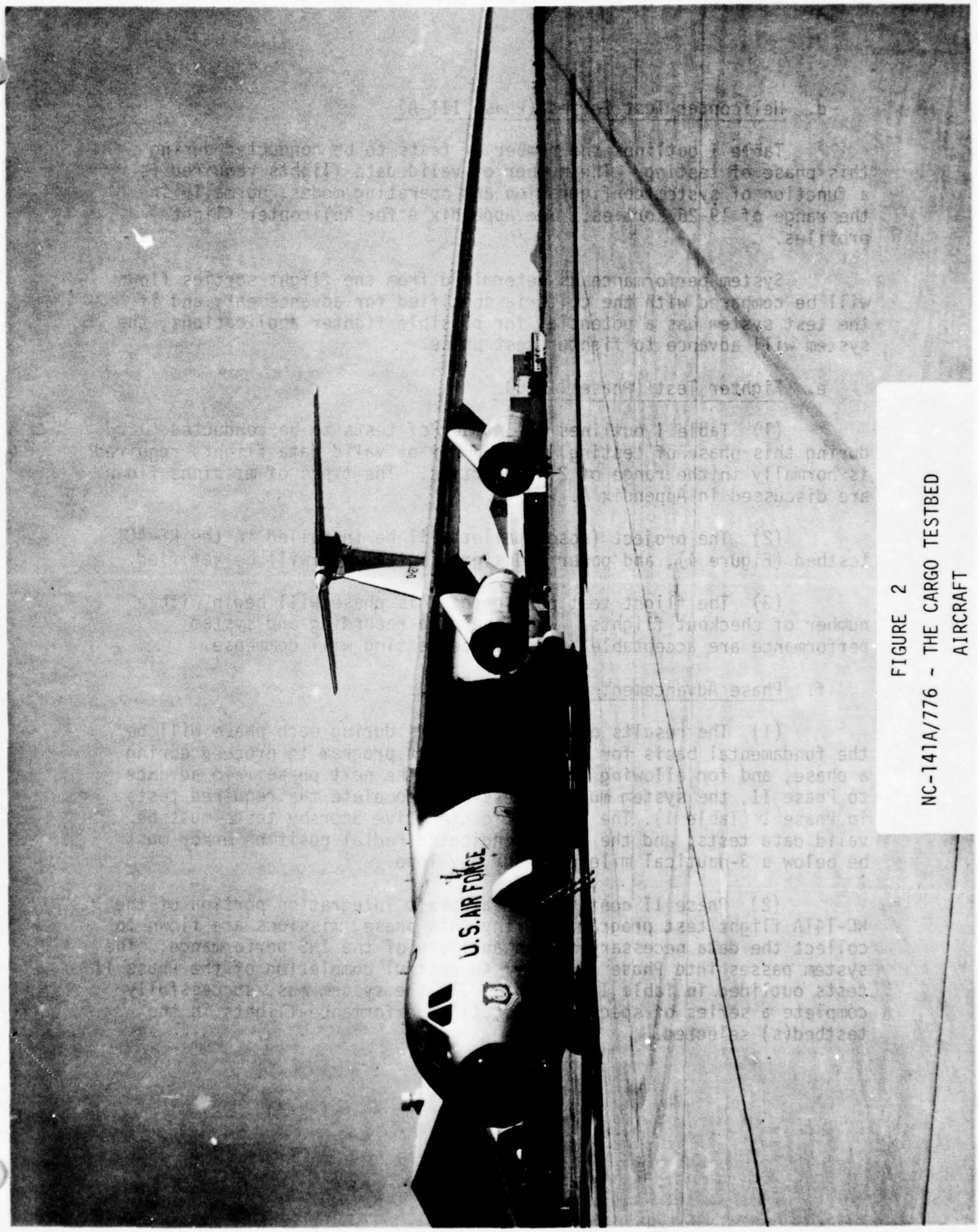


FIGURE 2
NC-141A/776 - THE CARGO TESTBED AIRCRAFT

d. Helicopter Test Series (Phase III-A)

Table I outlines the number of tests to be conducted during this phase of testing. The number of valid data flights required is a function of system configuration and operating modes, normally in the range of 19-26 sorties. See Appendix A for helicopter flight profiles.

System performance as determined from the flight sorties flown will be compared with the criteria specified for advancement; and if the test system has a potential for possible fighter applications, the system will advance to fighter test phase.

e. Fighter Test (Phase III-B)

(1) Table I outlines the number of tests to be conducted during this phase of testing. The number of valid data flights required is normally in the range of 21-24 sorties. The types of missions flown are discussed in Appendix A.

(2) The project (nose) pallet will be installed in the RF-4C testbed (Figure 4), and power and signal interfaces will be verified.

(3) The flight test portion of this phase will begin with a number of checkout flights. When the data recording and system performance are acceptable, performance testing will commense.

f. Phase Advancement Criteria

(1) The results of the valid tests during each phase will be the fundamental basis for allowing the test program to proceed during a phase, and for allowing advancements to the next phase. To advance to Phase II, the system must successfully complete the required tests in Phase I (Table I). The last two consecutive Scorsby tests must be valid data tests, and the system indicated radial position error must be below a 3-nautical mile per hour envelope.

(2) Phase II contains the aircraft integration portion of the NC-141A flight test program. During this phase, missions are flown to collect the data necessary for an analysis of the INS performance. The system passes into Phase III after successful completion of the Phase II tests outlined in Table I. In Phase III the system must successfully complete a series of special application performance flights in the testbed(s) selected.

FIGURE 3

UH-1H HELICOPTER READY TO LAUNCH
TEST MISSION

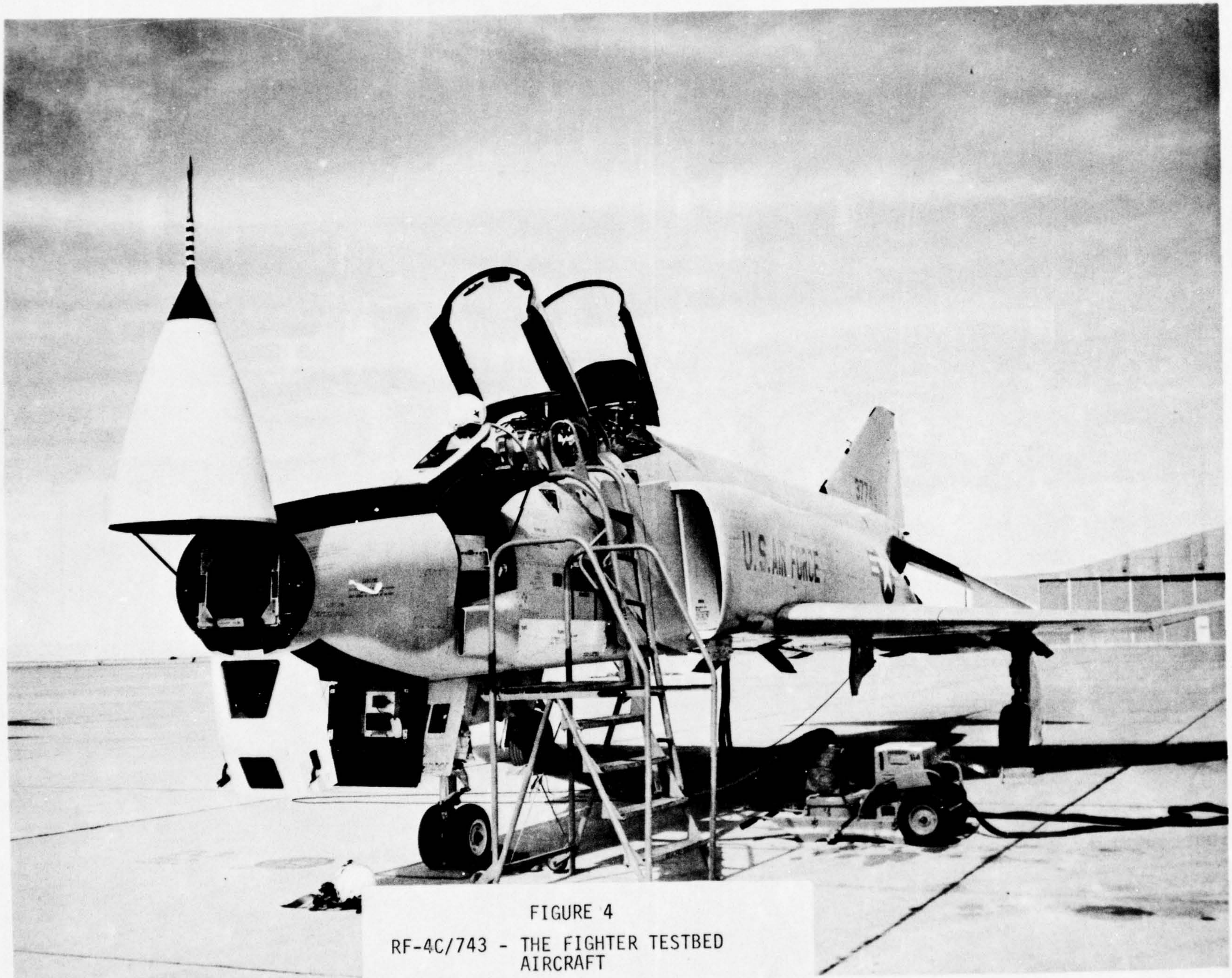


FIGURE 4

RF-4C/743 - THE FIGHTER TESTBED AIRCRAFT

(3) If the system repeatedly fails to meet any of the criteria for advancement into each phase, the system may be recalibrated as required and the test repeated. Should it be determined at any time during the test program that the system does not have sufficient merit to warrant further testing, the project will be terminated.

g. System Substitutions and Repair

(1) The primary purpose of verification testing is to evaluate the performance and operational suitability of the test system, or systems, as accurately as possible in a minimum amount of time. It is also Air Force policy to gather as much maintainability and reliability information as can be obtained during this test process. Consequently, the Air Force exercises strict control over verification test systems configurations. Multiple substitutions are avoided whenever possible, and repair or replacement of minor subcomponents is preferred to major component substitutions.

(2) Developmental test policies are not nearly as strict, and efforts are primarily confined to maintaining correct documentation.

7. FLIGHT TEST INSTRUMENTATION AND DATA COLLECTION

a. Instrumentation for any given project will depend to a large extent on the type, quantity and accuracy of data required.

b. System data will ordinarily be recorded on magnetic tape. The type of data collected may be separated into two categories. The first category is that required to determine quantitatively the system accuracy. Typically, position, velocity, and attitude data are of interest. The second category is that required for analysis and trouble-shooting the system. Data recorded for analysis purposes may be rather extensive for complex system, and may include any data available, internal or external to the inertial navigation system, which might aid in isolating individual system error sources.

c. In-flight reference data is ordinarily obtained from FPS-16 radars, cinetheodolites, DOVAP, on-board vertically stabilized camera, or CIRIS. Table II lists typical position, velocity and attitude accuracies and coverage available from these sources.

d. The CIGTF recently accomplished a highly significant increase in the C-141 in-flight reference capability with the in-house development of the Completely Integrated Reference Instrumentation System (CIRIS) (see Appendix B).

TABLE II

REFERENCE SYSTEMS AND TYPICAL SIGMA ACCURACIES AVAILABLE (1σ)

	Checkpoint	Radar	Cine	DOVAP	CIRIS
Position (ft)	100-500	50-200	15-25	N/A	13
Velocity (ft/sec)	N/A	2-10	0.5-1.0	.3	.1
Attitude (min)	N/A	N/A	N/A	N/A	3
Data Available	2-5 days	10-30 days	20-40 days	7-15 days	Real-Time
Weather Affects	Yes	No	Yes	No	No
Coverage Time (min)					
N-S Direction	>84	42	6	6	>84
E-W Direction	>84	84	4	4	>84

CIRIS output is available every second when generated post-flight and every five to ten seconds in real-time. The output is available in all three axis, and has the following accuracies (1 sigma):

Position	13 ft
Velocity	.1 ft/sec
Attitude	3 arc minutes

These accuracies exceed what is required for most guidance system tests, and is comparable to or better than cinetheodolite and laser ranging systems, and has many advantages not shared by these and other systems. A major characteristic of CIRIS is the fact that the velocity data is generated from acceleration and incremental position measurements rather than by position differentiation techniques that are inherently noise producing procedures. Thus, better quality velocity data is produced.

CIRIS was designed to provide continuous highly accurate reference data that is available over long flight paths in any direction. This capability is most important to navigation systems testing. Most navigation systems use inertial sensors on local level stabilized platforms that exhibit an oscillating error characteristic with an 84-minute period known as the "Schuler" period. Test missions are usually flown in one direction along a cardinal heading (east-west or north-south) to separate individual instrument (gyros and accelerometers) contributions to the system error accumulation. CIRIS supports these long flight tests anywhere within 150 nautical miles of land, due to a requirement for line-of-sight radio communication with ground-based transponders. CIRIS operation over wide areas and at diverse locations is a unique capability for a high accuracy reference system.

The availability of real-time high accuracy CIRIS reference data and digital processing have enhanced test capability by supporting tests in ways not formerly possible. For example, accurate all-weather flight path control, repeatable flight profiles, time-to-target predictions, and air-alignment data transfers have been accomplished by using CIRIS data. In addition, CIRIS hardware, including doppler radar and air data (barometric altitude), have been used as inputs to test systems.

CIRIS has significantly reduced the effects of scheduling constraints by supporting tests on weekends when airspace is available, and by allowing independence from the need to fly in restricted ranges. CIRIS has been used to instrument data acquisition for limited quick-response tests, and has minimized the need for immediate post-flight data reduction. Thus, significantly more testing can be accomplished and with better data quality control due to the visibility provided by the availability of CIRIS data processed in real-time.

e. Minicomputer Instrumentation

(1) Rapid advances in the state-of-the-art of digital computers have brought revolutionary changes in test instrumentation. Significant reduction in the size and cost of general-purpose digital computers (minicomputers) has resulted in extensive use of these minicomputers to acquire data directly from the test item and use the computation capabilities to scale and display the test item data on a real-time basis. The development of low-cost graphic terminals, such as the Tektronix 4010 series, has enabled us to display the test item data both alphanumerically and graphically. In particular, key parameters which can indicate to the test engineer the functional operation of his test item can now be displayed in a manner which makes it much easier to analyze the performance of his system. This particular feature of the instrumentation is extremely important when the test schedule is short and decisions regarding additional test, or software/hardware modifications must be based on observed test item performance. In addition, each pallet is equipped with a digital recorder so that all of the test item data can be recorded for post-flight reduction and analysis.

(2) The improvements have not been limited to the flexible and reliable data acquisition, control and display capabilities of computer control instrumentation, but has been an important tool to provide what is referred to as "quick-look" capability. "Quick-look" is essentially the ability to obtain timely information concerning the results of a test (that has been recorded on magnetic tape) which affect the schedules and/or quality of further tests.

(3) The time constraints imposed on flight testing due to aircraft scheduling and support coordination affect the data acquisition equipment and the test system performance. Each test mission records this data on magnetic tape. This information can impact decisions to repair equipment, alter mission schedules, perform calibrations, change test plans, repeat or change test profiles and numerous other decisions that lead to timely and cost effective testing.

(4) Software has been developed that effectively uses the capabilities of minicomputers and peripherals post-flight in a ground station to provide the "quick-look" capability described. It is important to note that this post-flight capability does not duplicate the real-time data display which may also affect decisions of a similar nature, but is totally dependent on recorded data which must be used for system evaluation by test analysts. The simplicity of operation can best be illustrated for a recent test program. Thirty minutes after the first data tape had been recorded, a plot of position versus time had been generated.

(5) The minicomputer is an effective tool for generating needed information in a timely manner. Analysis of data tapes for the purpose of test quality control had advanced the flight test capability providing significant improvements in response time to events that might have otherwise gone unnoticed prior to the next mission.

8. TESTBED AIRCRAFT

Flight testing efforts over the last several years revealed that a new type of testbed aircraft (TBA) was needed. In the past, precious time was wasted when the aircraft had to be modified to accommodate a new test item. Modifications of aircraft are a time-consuming operation, since every modification must be carefully controlled for flight safety, and design procedures are so detailed that each modification takes considerable time. An increasing workload and the reduction of available aircraft testbeds made the design of a new TBA essential. This new aircraft was designed to incorporate a palletized concept so that the testing of any new system would require a minimum amount of modification to the aircraft. In addition, the TBA can accommodate testing of several test systems simultaneously so that available aircraft time can be used more cost effectively.

A C-141 aircraft, modified to allow the CIGTF to test up to five different systems simultaneously, with a minimum amount of aircraft downtime, was designed to satisfy the TBA requirements. The key element in the design was the decision to place all test items and test instrumentation on aircraft pallets. Each of five pallet stations on the aircraft is equipped with an interface junction box for power and signal transmission to the pallet. Thus, the interface between the aircraft and test item is reduced to a set of cables that provide aircraft power (115 volts, 400 Hz, and 28 volts dc), and signal data (IRIG time, aircraft intercom and station-to-station data exchange). Additionally, to minimize test downtime if a test item has to be removed from the aircraft, the test item pallets were designed to facilitate quick removal and installation. Figure 5 depicts the installation of a pallet on the aircraft. Installation or removal takes about 15 minutes per pallet, and all five pallets can be removed and reinstalled in less than three hours.

a. Testbed Instrumentation

To facilitate testing of the test specimen, common instrumentation is permanently installed in the TBA. These include a vertically stabilized camera for photographic position checkpoint data; master IRIG time generator for precision time reference; air data computer

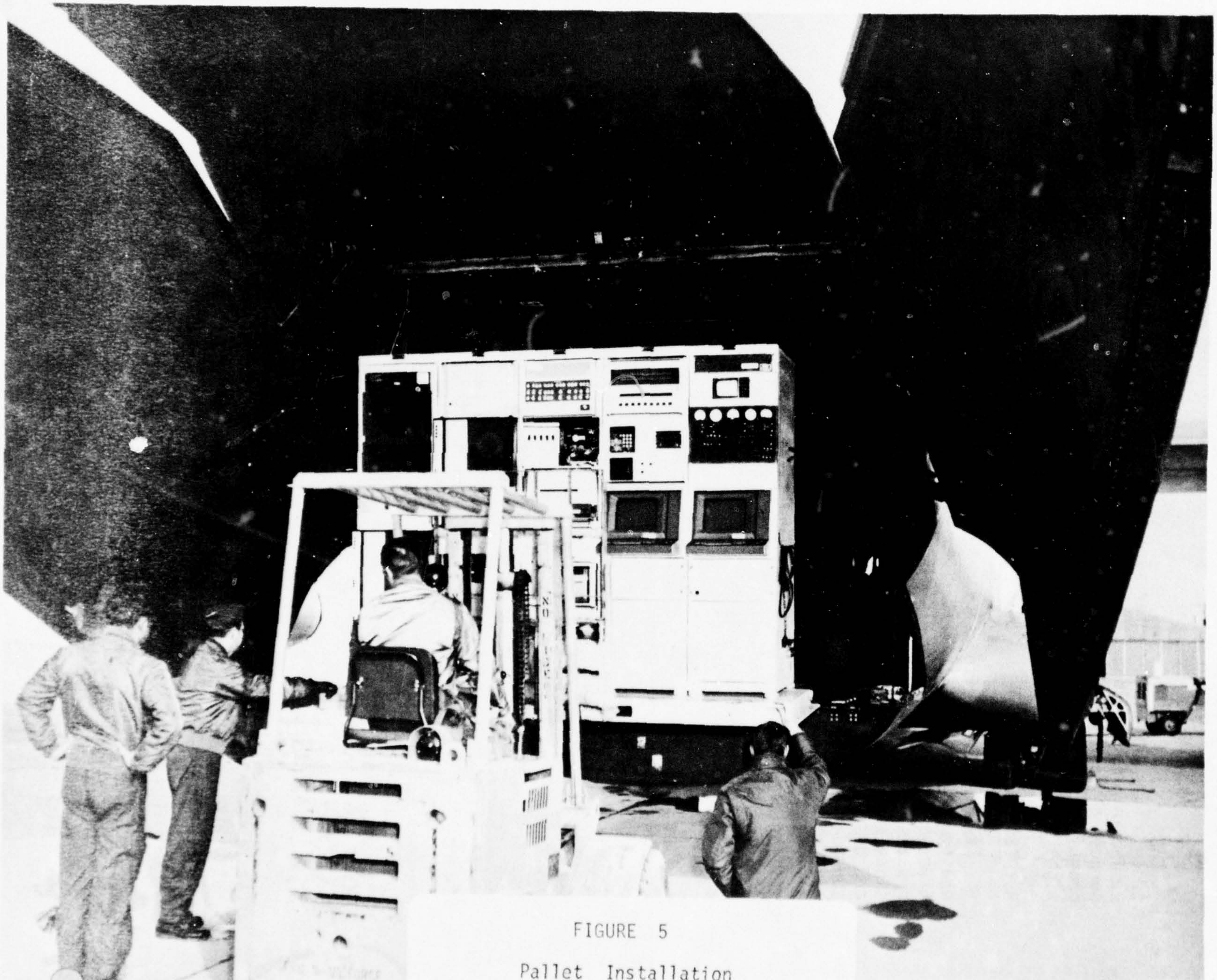


FIGURE 5

Pallet Installation

for barometric altitude, true air speed, and outside air temperature; and a doppler radar for velocity information. The vertically stabilized camera and associated optical sighting displays (modernized drift sites) allow the test team to take reference data while flying, and generate quick-look plots that can be used to determine if gross errors exist in the test specimen. This combination of instrumentation provides a wide range of instrumentation data that can be obtained via the signal connector (located in each pallet junction box) without any requirement to modify the aircraft or install duplicate instrumentation devices on each test item pallet.

b. Test Item Pallet

A general test item pallet configuration provides flexibility of data acquisition and display or test item equipment on each pallet, thereby minimizing the time to implement design changes. Items that are common to most tests were identified and allocated space on the pallet. These items include a minicomputer, 400/60-Hz power converter, IRIG time generator, magnetic tape recorder, operator's display, and an air conditioner (Figure 6). The IRIG time generator is synchronized with the master generator before take-off to provide redundant timing or to repeat and display a visual readout from the master generator. Cooled air is provided for the test item (if required) and other pallet instruments.

9. DATA REDUCTION, ANALYSIS AND REPORTING

All data are processed and controlled by Air Force personnel at the Central Inertial Guidance Test Facility except range tracking data which are processed by the US Army at White Sands Missile Range, New Mexico, Fort Huachuca, Arizona, and at the Space and Missile Test Center, California.

a. System Data Reduction

(1) Systems normally output data in digital form. The data are recorded on magnetic tapes making it possible to do the necessary processing directly using ground based computational equipment. If a system outputs data in analog form, these data are first digitized at the CIGTF prior to data reduction.

(2) When radars or cinetheodolites are used as the position and velocity reference, system and reference data are normally compared at 10 second intervals. When a vertical camera is used for reference instrumentation, system position data are needed additionally at checkpoint times (usually every three to five minutes).

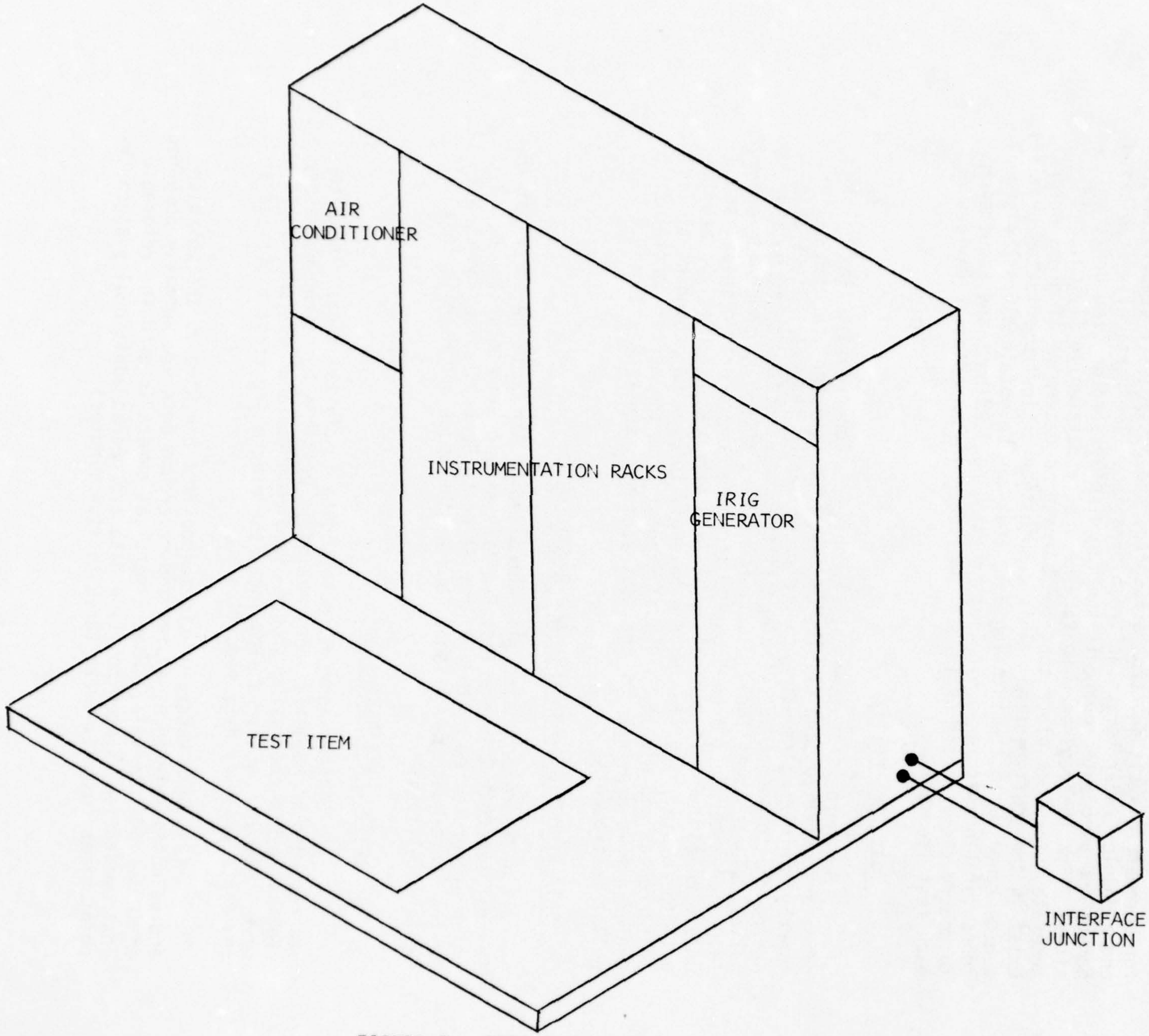


FIGURE 6. TEST ITEM PALLET.

(3) The length of time required to reduce system data varies considerably depending on the method of data recording. Analog tapes usually require a week or more to digitize. Digital tapes may be placed directly on the land based computer for further reduction. Hand recorded data are usually punched onto cards within one to two days for further reduction.

b. Reference Data Reduction

(1) During on-range flights, radar data are magnetically recorded at 10 or 20 frames per second. The data are thinned to one frame per second and a single station solution is used to find reference latitude, longitude, and MSL altitude. Cinetheodolite data are usually recorded at one frame per second. Film from two or more cinetheodolites are reduced using a multiple station solution to obtain reference latitude, longitude, and MSL altitude.

(2) During off-range flights, aerial photographs are made of surveyed ground checkpoints. Miss distances are read from the film and added to checkpoint coordinates to obtain reference latitude and longitude.

(3) The time required for reference data reduction is approximately as follows: 10 to 30 days for radar data, 20 to 40 days for cinetheodolite data, 2 to 5 days for photo data, CIRIS data within hours after flight. The time required over and above the minimum quotes is primarily a function of the range workload and problems encountered in reducing the data.

c. Error Data Reduction

(1) Position error information is obtained by computing the difference between system indicated data and reference data. Time synchronization is achieved by recording IRIG-B time with both system and reference data. Range reference time is derived from a master range timing station through land line and microwave relay. The system timing reference is recorded directly from an onboard IRIG-B time code generator. Using this method, a time synchronization within one millisecond between range reference data and system data is achieved.

(2) During off range flights, system data are recorded as close to checkpoint photographs times as possible. Proper timing for error plots is accomplished in analysis and data processing.

d. Number of Samples

(1) The purpose of testing is to collect sufficient data to reasonably estimate how the system, indeed any article under test, will perform in routine service. The more tests that are run, the more confidence can be given to the results. Statistics provide a quantitative measure of this confidence. The following is a short discussion of the statistics used to determine the least, yet statistically valid, number of tests that should be performed:

(a) Suppose N representative samples, the test measurements, are made of the variable of interest, say X. Then the sample Circular Error Probable, $\widehat{CEP}$, and sample standard deviation, S, are easily calculated. These statistical measures apply to the test results only. To determine the $\overline{CEP}$, and σ for the entire population (the same measurement applied to operational systems) requires the application of Statistical Analysis. These statistics have been simplified in Figure 7 for the ratio $\overline{CEP}$ to $\widehat{CEP}$.

(b) Assume the same sample of N gives a value of $\widehat{CEP}$. From Figure 7, the value $\overline{CEP} \leq K_{CEP} \widehat{CEP}$ is determined to any level of confidence desired. For example, assume N = 6, $\widehat{CEP}$ = 1.0, then:

$\overline{CEP} \leq 1.04$ with 50% confidence,

$\overline{CEP} \leq 1.22$ with 75% confidence,

$\overline{CEP} \leq 1.60$ with 95% confidence.

(c) Furthermore, with N - 14 samples and $\widehat{CEP}$ = 1.0 (for simplicity, recognizing the computed CEP would probably change) Figure 7 gives:

$\overline{CEP} \leq 1.01$ with 50% confidence,

$\overline{CEP} \leq 1.12$ with 75% confidence,

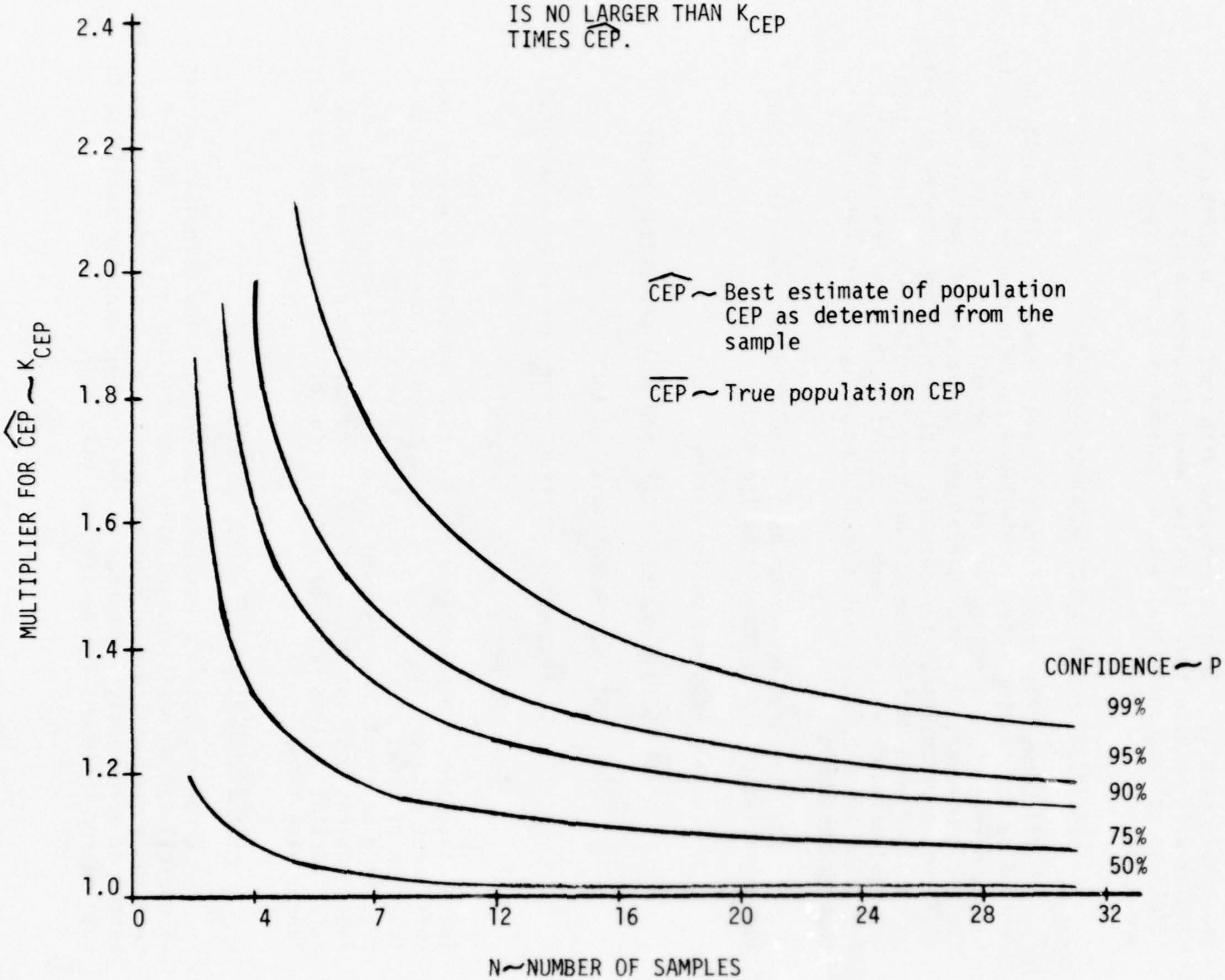
$\overline{CEP} \leq 1.30$ with 95% confidence.

(d) Similar analysis can be applied to other measures of the sample statistics such as mean and standard deviation. However, each one has a separate confidence curve such as given in Figure 7 for CEP.

(2) For good statistical confidence, a large number of samples should be used (20, 30 or more). In practice this would be prohibitive in cost and furthermore, the "value" of additional tests (in terms of improved confidence) reduces rapidly as the number of tests increases.

FIGURE 7

PROBABILITY (P) THAT $\overline{CEP}$ IS NO LARGER THAN K_{CEP} TIMES $\widehat{CEP}$.



For these reasons and from the experience of many test programs, the rule of thumb has been adopted that six (6) samples are required for reasonable results. This is tempered with cost and occasionally less samples will be accepted. Likewise, when the opportunity presents itself to collect additional data at minimum cost, more samples are used.

e. Cumulative Radial Error Accuracy Results

(1) Cumulative radial error accuracy results will usually be derived by considering tests in different environments (static, Scorsby, C-141, RF-4C, or helicopter) as separate ensembles. Tests may be combined, however, if system performance is not significantly affected by different environments. For example, static and Scorsby tests may often be combined when making ensemble accuracy calculations. If more than one navigation or alignment mode is tested in the same environment, the tests in each individual mode will normally be considered as a separate ensemble.

(2) Measures of performance calculated for inertial systems for ensembles of six or more tests include:

(a) Mean and median errors.

(b) 50th percentile, CEP, and 90th percentile error.

(c) 85% confidence limits on the CEP.

(d) Least squares position error rate (when meaningful).

(e) RMS error (when meaningful).

These statistics are calculated for position and velocity errors when sufficient data are available. Items a through c are calculated as a function of time, usually at 5 minute intervals. Items d and e are presented as single numbers when the statistics are meaningful. A least squares position error rate will ordinarily be presented only for pure inertial systems which have a position error growth which is nearly linear with time.

f. Estimation of System Error Sources

Error analysis is focused on determining the principal sources of overall system position, velocity, and attitude errors. The techniques used will depend upon the particular system mechanization. The extent of error analysis depends on the time and manpower available to develop and implement the desired analysis.

g. Test Event Reports

Test data and preliminary test results are available to the customer as soon as possible after each test. Normally, a quick-look error plot, to include any significant occurrences, is available immediately after each test event.

h. Data Packages

For test programs which require performance accuracy data to be released as soon as possible, data packages will be prepared two weeks after each phase of testing.

i. Final Report

(1) After the completion of testing, a final report is prepared. This will contain all results of the test program, including the data presented previously in data packages. Information reported will customarily include:

(a) Overall test program review.

(b) Test objectives and procedures.

(c) Physical characteristics of the system.

(d) Performance accuracy results.

(e) Error analysis results.

(f) Operational suitability comments.

(g) Data reduction and analysis techniques.

(h) Test instrumentation.

(i) Maintenance and repair log.

(2) Position and velocity accuracy results will include plots of the following quantities as functions of time in the navigation mode:

(a) For each flight--latitude, longitude, radial position and velocity errors.

(b) Cumulative results--

1 Mean, median, 50th percentile, and 90th percentile of radial position and velocity errors;

2 CEP and 85% confidence limits on the CEP of radial position and velocity errors;

3 a composite of radial position and velocity errors for all valid data flights in each phase.

j. Data Distribution and Classification

(1) Initial distribution of all data and test results are controlled by CIGTF. Distribution lists (designated by the customer/CIGTF) will be contained in the specific system test plan. Contractor proprietary rights are observed.

(2) Test data and results are accorded a security classification commensurate with the program and system under test.

10. RECENT TEST PROGRAMS AT THE CIGTF

a. Since aircraft inertial navigation systems flight testing began at the CIGTF in 1964, 40 systems have undergone verification or developmental testing. Six systems are currently in active testing or in report. Appendix C contains a detailed tabulation of the test efforts. The following is a brief description of several verification and developmental tests recently completed at the CIGTF.

(1) Singer-Kearfott SKN-2400 INS

The Singer-Kearfott SKN-2400 INS was subjected to verification testing February 1973 until April 1974. The system was flown in NC-141A, UH-1H and RF-4C aircraft. A total of 178 flying hours and 764 operating hours were accumulated during the test. During the testing several production line assembly technique problems were identified and corrected. The helicopter testing identified a low frequency sensitivity that was easily corrected. The SKN-2400 was found to be easily maintainable and in the "one mile per hour" class. It was successfully verified for the cargo, helicopter and fighter aircraft. The SKN-2400 has been selected as the F-16 INS, and is proposed for the C-141 retrofit program.

(2) Litton LTN-72 INS

The Litton LTN-72 INS, an in-production ARINC specification INS, was subjected to verification testing from January through August 1975. The LTN-72 was flown in the NC-141A only, as its application is limited to cargo/bomber type aircraft. The LTN-72 INS was flown in the CONUS and in Alaska. The system was found to be less than one mile per hour and was successfully verified for cargo type aircraft. The LTN-72 is being proposed for the C-141 retrofit program.

(3) B-1 Navigation System

The B-1 Navigation System, consisting basically of the LN-15S platform, the AN/APN-185 doppler radar, the AN/APN-194 radar altimeter, and the SKC-2070 computer was subjected to development testing

between June 1974 and August 1975. The objective was to check out the navigation portion of the Offensive Flight Software. The test program was originally 30 flights, including six in Alaska. As the program progressed, problems with the APN-185 doppler radar precipitated additional flights. The B-1 System Program Office (SPO) requested a special series of doppler radar tests to be performed. Specifically, four APN-185 antennas were to be calibrated (for B-1 aircraft No. 3 use) and simultaneous performance data was to be collected on the APN-185, APN-200 and APN-206 doppler radar. This series was completed using the CIGTF CIRIS as the velocity reference. The B-1 SPO decided the APN-200 was a potential candidate for their use and requested a series of tests with the APN-200 coupled to the B-1 Navigation System. As a result of B-1 Navigation System/APN-200 doppler radar testing, the B-1 SPO selected the APN-200 doppler for the production B-1. The 84 total flights of the B-1 Navigation System on the CIGTF testbed aircraft helped solve many hardware and software problems, thus saving the B-1 test aircraft from many navigation system problems.

(4) <u>Honeywell Laser Inertial Navigation System (LINS)</u>

The Honeywell LINS, a ring laser gyro/conventional accelerometer INS, was subjected to limited developmental flight testing at the CIGTF from April through June 1975. The system was flown in the CONUS and in Alaska. The system performance appears to be in the "one mile per hour" class, and the purpose of the test, to demonstrate the application of ring laser gyros to aircraft inertial navigation systems, was accomplished.

11. CURRENT AND FUTURE INS TEST PROGRAMS

The following is a list of current and future CIGTF INS test programs. These are separated by type of test.

a. <u>Current Programs</u>

(1) Verification

(a) Hamilton Standard HSDN-1020 Strapdown INS

(b) Singer-Kearfott SKN-3000 Strapdown INS

(c) Litton LN-40 INS

(d) Litton LTN-72/Ryan APN-213 Doppler-Inertial Navigation System

(3) Honeywell SPN/GEANS INS

(2) Developmental

(a) Sperry Radiometric Area Correlator Guidance (RACG) System

(b) E-Systems Cruise Missile Guidance System

(c) McDonald Douglas Cruise Missile Guidance System

(d) Northrop NIS-210-24 Attitude and Velocity System

b. Future Programs

(1) Verification

(a) Autonetics N-77 INS

(b) Autonetics MICRON INS

(c) Standard Inertial Navigation System(s)

(2) Developmental

(a) Advanced ICBM Technology (MX)

(b) Precision Guided Re-entry Vehicle

c. Other Related Efforts

The CIGTF has been tasked by Hq USAF to perform doppler performance testing for upcoming doppler radar buys/retrofits for Air Force cargo/bomber aircraft.

12. SUMMARY

In summary, the 6585th Test Group's Central Inertial Guidance Test Facility (CIGTF), since being designated as the DOD focal point for testing of inertial navigation systems, has built up a wealth of experience in guidance system flight testing. Since aircraft inertial navigation system flight testing began at the CIGTF in 1964, 40 systems have undergone verification or developmental testing. During this period, the CIGTF has developed advanced instrumentation systems, including a precise reference system (CIRIS), adapted a palletized testbed concept, and established new test methods and data analysis techniques. This development, with a hard core of experienced personnel, has produced an unequalled capability for test and evaluation of aircraft inertial navigation systems.

APPENDIX A

REPRESENTATIVE FLIGHT PATHS

I. CARGO CHECKPOINT FLIGHT PATHS

a. In Phase II testing, the system is installed and flown in an NC-141A testbed aircraft. Following initial shakedown sorties, data flights are performed over specially designed flight paths where accurately surveyed checkpoints are photographed using a vertically stabilized camera to provide reference information.

b. The reasons for including the transport phase even for systems intended for fighter applications are as follows:

(1) The transport usually provides a more economical vehicle in which to checkpoint system performance. This is especially true for systems with complex software mechanizations.

(2) Longer flight times can be provided more economically in the transport than in the fighter. Routes (see Figure A-1) over precision surveyed checkpoints exist across the entire country providing a transcontinental flight test capability. Established checkpoints routes are also located in Alaska for high latitude tests.

(3) Present fighter aircraft require the extensive use of range facilities for radar tracking. Transport aircraft can often use off-range vertical photography as a position reference. This can be especially efficient for the checkout portion of system testing, and is often accurate enough for verification testing.

(4) Continuous radar coverage is available from Holloman AFB to the West Coast using the tracking facilities of White Sands Missile Range, Ft. Huachuca, AZ, and SAMTEC, Vandenberg AFB, CA.

II. HELICOPTER FLIGHT PATHS

Two basic types of flight profiles are flown during this test phase: Both North-South and East-West navigation profiles, and terrain mapping profiles. The navigation flight profiles will be flown in order to obtain baseline navigation data in straight and level flight. These flights are made at 750-1000 foot altitudes above ground level. They are made with 180° turns coinciding with a half Schuler period (42 minutes). The terrain mapping profiles are designed to simulate operational conditions as closely as possible. Specific maneuvers include: low level cruising, low level hover, landing between maneuvers, autogyro descent from altitude, attack and evasion profiles, and mapping profiles. The normal duration of each mission is 1 1/2 - 2 hours. Figure A-2 is an outline map of the helicopter flight paths.

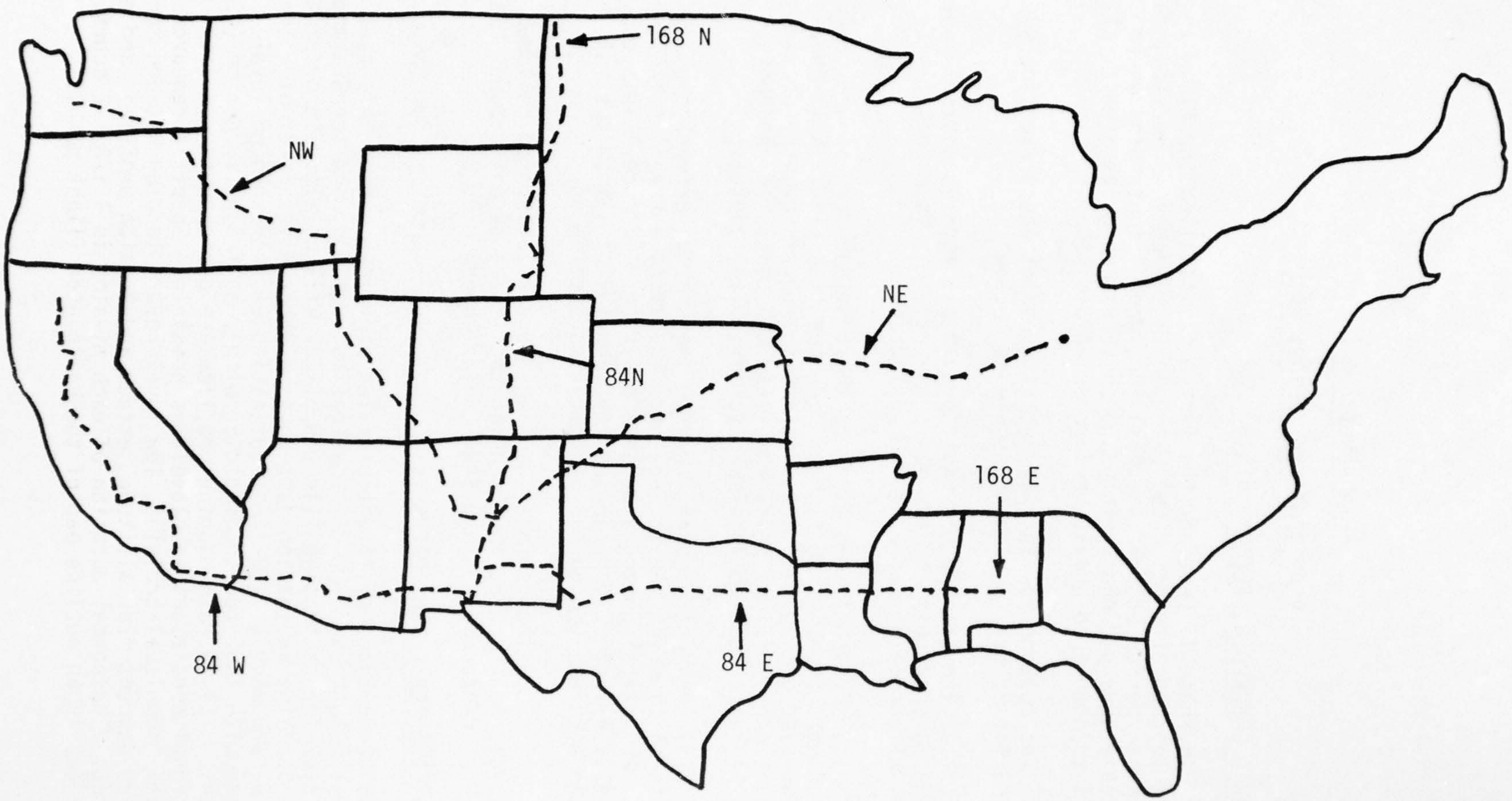


FIGURE A-1: CHECKPOINT PATHS

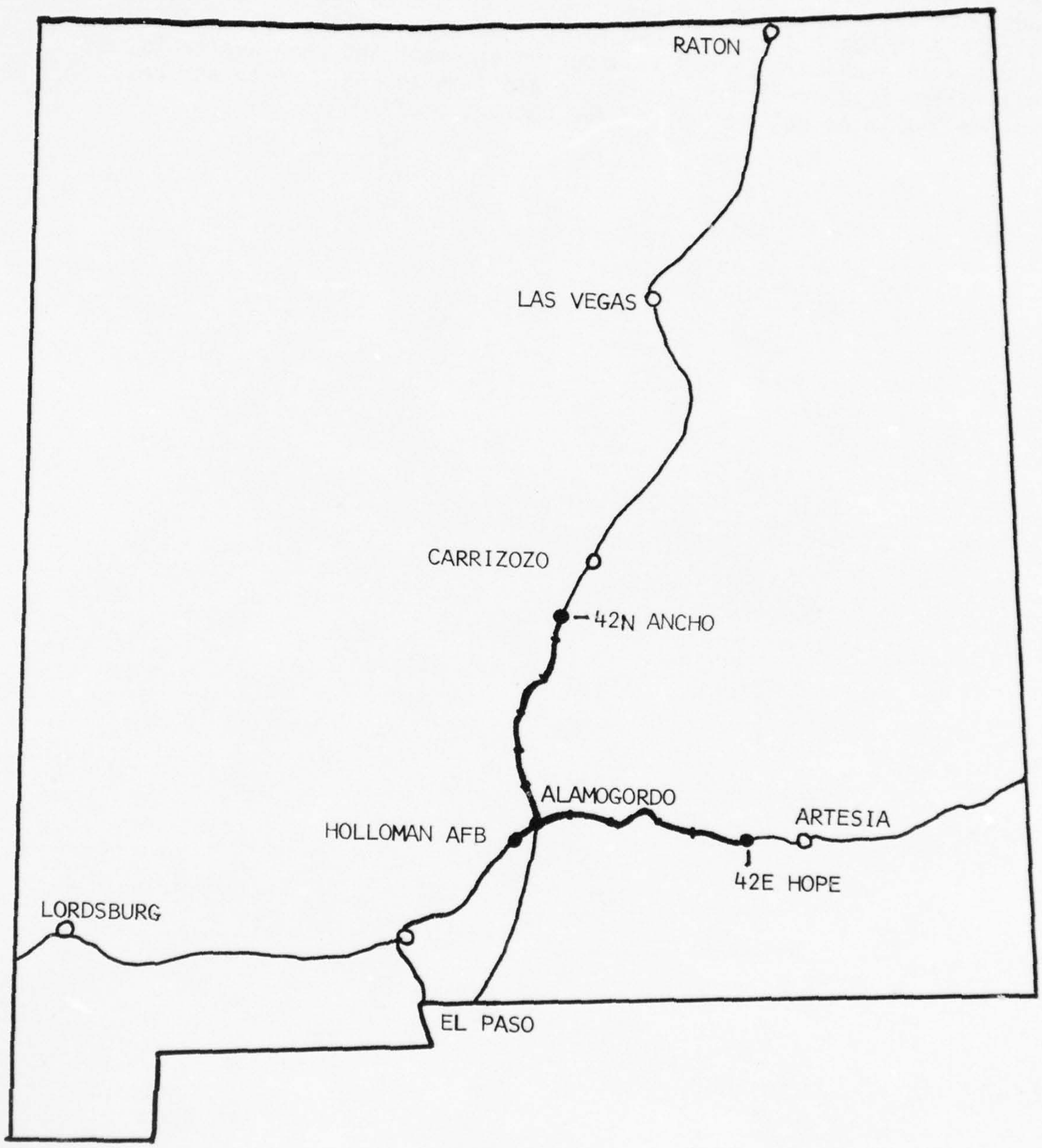


FIGURE A-2
HELICOPTER CHECKPOINT
FLIGHT PATHS

III. FIGHTER FLIGHT PATHS

Currently, the only available flight path for fighter aircraft is a west-east path from Holloman. West is the only direction with adequate radar coverage for the required 42 minute legs. The fighter aircraft is the limiting factor for the duration of the legs. A CIRIS mounted in a centerline pod is under development and when available, will allow fighter flights to be, in addition to west, north and east. Figure A-3 is an outline map of the current profile.

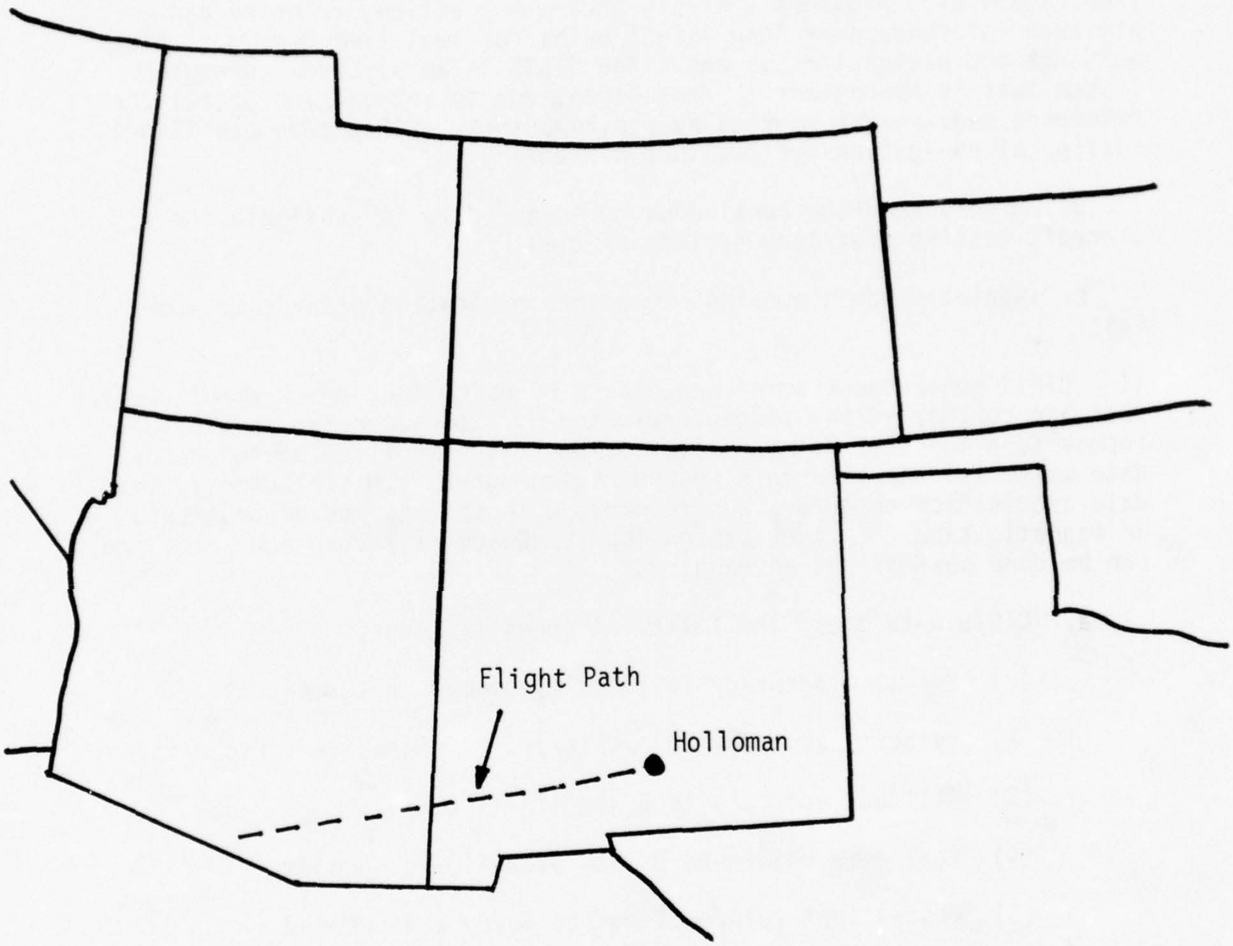


FIGURE A-3
FIGHTER FLIGHT PROFILE

APPENDIX B

DESCRIPTION OF THE COMPLETELY INTEGRATED REFERENCE INSTRUMENTATION SYSTEM (CIRIS)

I. The Completely Integrated Reference Instrumentation System (CIRIS) (see Figure B-1) provides a highly accurate position, velocity and attitude reference over long flight paths for real-time use in testing guidance and navigation systems. The CIRIS is an airborne automated system that is operationally independent due to integration of all the reference measurement sources by minicomputers. CIRIS advances flight testing of navigation systems in two areas:

a. Highly accurate continuous reference data is available for aircraft testing over long periods of time.

b. Real-time data provides immediate evaluation of systems under test.

II. CIRIS generates the reference data by using four measurement devices that are controlled and time-coordinated by a minicomputer to provide inputs to a 15-state Kalman filter. The real-time filtered reference data which is generated in a second minicomputer is distributed to test data acquisition computers and recorded with the raw measurement data on magnetic tape. Further processing (backward filtering and smoothing) can be done post-flight as required.

a. CIRIS data meets the following specifications:

(1) Position accuracy to 13 ft (1 sigma) in three-axis.

(2) Velocity accuracy to .1 ft/sec (1 sigma) in three-axis.

(3) Attitude accuracy to 3 arc min (1 sigma).

(4) Real-time reference points every 10-15 seconds.

(5) Post-flight reference points every 2-4 seconds.

(6) Continuous reference for longer than 84 min in any direction (limited only by transponder availability).

This data can be used for time correlated comparison with systems under test in their data acquisition computers. Real-time display and plot generations of test and reference data provide laboratory capabilities in a flight test environment.

b. The measurement hardware includes an inertial navigation system stabilized by barometric altitude from an air data computer, a doppler, radar, and a precision radio range/range-rate system. The inertial

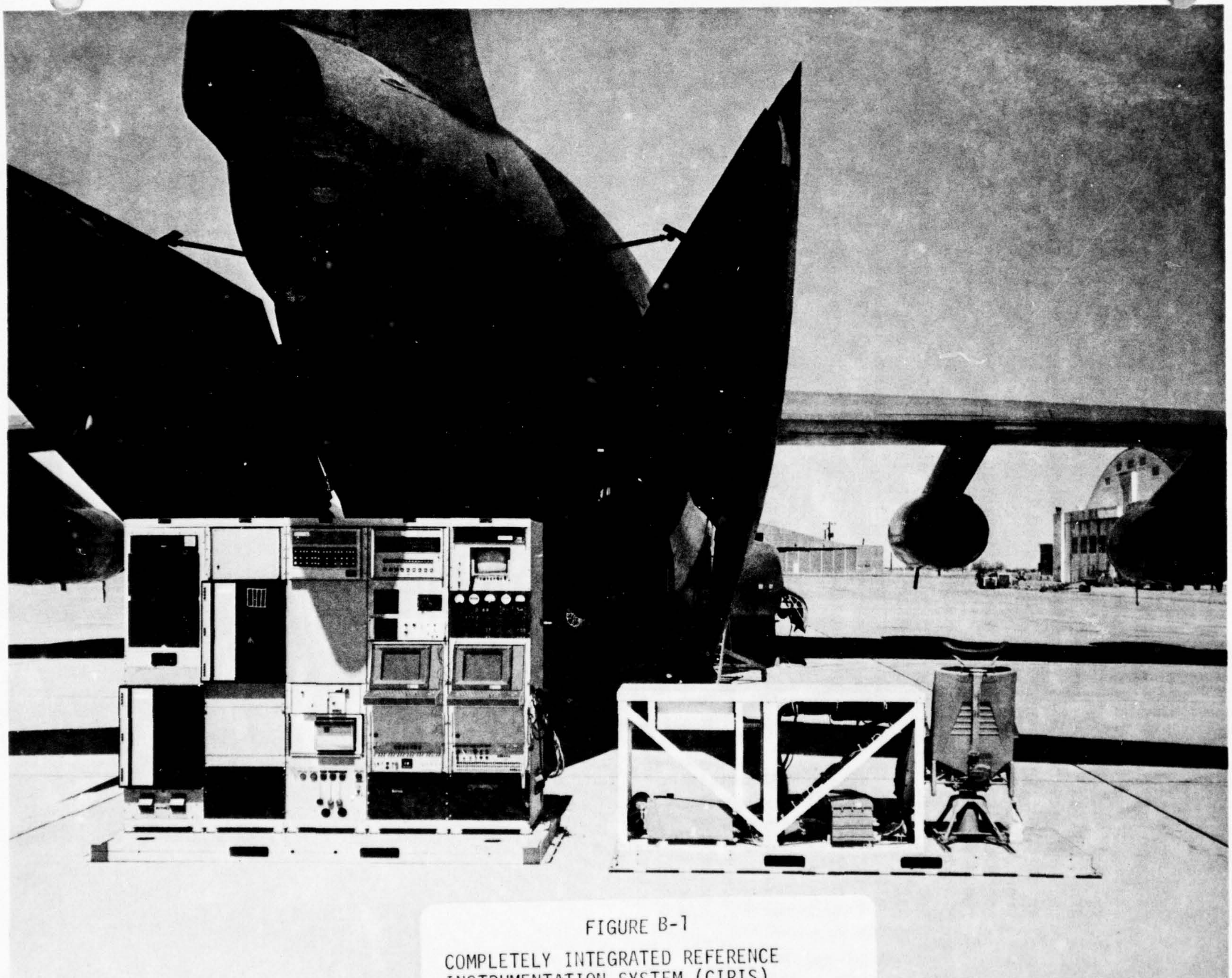


FIGURE B-1

COMPLETELY INTEGRATED REFERENCE INSTRUMENTATION SYSTEM (CIRIS)

system data is used in the filter as continuous reference for data propagation and reference for the filter error states. The error states are updated by incorporation of barometric altitude, doppler velocities, and precision range and range-rates to precisely surveyed ground sites. The CIRIS accuracies are directly dependent on the measurements obtained from the range/range-rate system which includes an airborne interrogator that is used to selectively interrogate each ground-base transponder every two seconds. A set of the four transponders nearest the current aircraft location is used to provide one redundant measurement in a time-phased triangulation scheme. The transponders and associated omnidirection antenna are portable and are designed for remote operation. They are deployed in a triangular pattern separated by approximately 150 miles in a line along the flight path. CIRIS degradation can occur when flight paths leave areas of radio range coverage which extends to 200 nautical mile line-of-sight. Incorporation of doppler radar data will minimize degradation until radio coverage is resumed.

III. In summary, the CIRIS has provided a new dimension to navigation system flight testing. The advances in reference accuracies have influenced the methods of data analysis, new improved methods are being investigated. Real-time data comparison can shorten test duration and the operational independence has had a positive affect on schedules for testing state-of-the-art aided inertial navigation systems which require this precision reference.

APPENDIX C

INERTIAL NAVIGATORS FLIGHT TESTED AT

THE CENTRAL INERTIAL GUIDANCE TEST FACILITY

This Appendix contains a tabulation of the inertial navigation systems tested or currently under test at the CIGTF.

TEST CODE: D=DEVELOPMENTAL V=VERIFICATION ::=CURRENTLY UNDER TEST

APPENDIX C

INERTIAL NAVIGATORS FLIGHT TESTED AT THE CENTRAL INERTIAL GUIDANCE TEST FACILITY

PRO GRAM	TYPE OF SYSTEM	SHORT TITLE	TEST CODE	CONTRACTOR	TYPE OF PLATFORM	GYROS NR	GYROS TYPE	ACCELEROMETERS NR	ACCELEROMETERS TYPE	TYPE OF COMPUTER A=ANALOG D=DIGITAL		TEST ENGINEER	TEST START	DDC ACQ NUMBER	
663E	MINIATURE INERTIAL	MINS	D	GPI	4-GIMBAL	3	KING II	3	KEARFOTT 2401	A		MR JAMES	1964		
663	INERTIAL NAVIGATOR	XN-16	D	AUTONETICS	4-GIMBAL	2	G-9	2	UM-8	D	VERDAN	LT HOOTEN	1964		
663	STELLAR INERTIAL DOPPLER	SIDS	D	LITTON	4-GIMBAL	2	G-300G	3	A200D	D	C-900	CAPT KUROWSKI	1965	AD383404	(C)
698	MARK II-INS	ASN-47	V	A-C	4-GIMBAL	3	SDF25 IRIG	3	GG-177B	D	MAGIC II	MAJOR ULSHAFER	1965		
698	MARK II-INS	LN-14	V	LITTON	4-GIMBAL	2	G-280	3	A200D	A	NCU	CAPT FOSSETT	1965		
698	MARK II-INS	HIPERNAS III	V	BELL	4-GIMBAL	2	BRIG IV	3	MOD-VIII	D	L-90-1B	MAJ ERI	1965		
698	MARK II-INS	LCI	V	GPI	4-GIMBAL	2	GYROFLEX	1	KEARFOTT 2414	D	DYDAN	MR JAMES	1965		
698	MARK II-INS	NIS-105	V	NORTRONICS	FLIP	3	GI-K7	3	AP-E4-10B	D	NDC-1050	CAPT KUROWSKI	1965		
698	MARK II-INS	N-16	V	AUTONETICS	4-GIMBAL	2	G-9	2	UM-8	D	D26J	LT HOOTEN	1965		
921	INERTIAL NAVIGATOR	LN-15	V	LITTON	4-GIMBAL	2	G-300G	2	A-200D	D	C-220	CAPT SORENSEN	1966	AD379888L	(C)
653	INERTIAL NAVIGATOR	PACE II	D	MIT	4-GIMBAL	3	2FBG-9F	3	16 PIGA G	D	VERDAN	CAPT ROROHA	1967	AD389179L	(C)
5201	LOW-COST INERTIAL	LOCATING	D	AFAL	4-GIMBAL	2	GYROFLEX	2	AUTONETICS/ KEARFOTT	D	NORTRONICS	MR JOHNSON	1967	AD810629L	(U)
698DF	STRAPDOWN INERTIAL	SIGN-III	V	HONEYWELL	STRAPDOWN	3	GG-334A	3	GG-177	D	HDC-501M	CAPT ROROHA	1968	AD503083	(C)
688G	INERTIAL NAVIGATOR	LTN-51	V	LITTON	4-GIMBAL	2	G-1	2	A-1	D	LC-720	MR JOHNSON	1968	AD507674L	(C)
8222	FLIGHT REFERENCE	FRSS	D,V	TELEDYNE	4-GIMBAL	2	TELEDYNE AIR BEARING	3	SINGLE AXIS	D	DDA	MAJ ULSHAFER	1968	AD843543L	(U)
921B	INERTIAL NAVIGATOR	P3C	V	KEARFOTT	3-GIMBAL	2	MOD II GYROFLEX	1	KEARFOTT 2414	D		CAPT KUROWSKI	1968	AD844809L	(U)
410A	INERTIAL DOPPLER	C-5A	D,V	NORTRONICS	FLOATED BALL	3	G1-K7G	3	KEARFOTT 2401	D	NDC-1051A	CAPT SORENSEN	1968	AD867681L	(U)
140A	CARRIER ACFT EQUIPMENT	SRAM(LN-15S)	D,V	BOEING/ LITTON	3-GIMBAL	2	G-300G2	3	A-200D	D	AUTONETICS	CAPT WOOD	1968	AD516448L	(S)
140A	AIRBORNE VEHICLE EQUIPMENT	SRAM	D	BOEING/GPI	4-GIMBAL	2	MOD-017 GYROFLEX	2	2401 & 2414	D		CAPT WOOD	1968	AD507564	(S)
139A	AMSA-INS	ASN-47	D	A-C	4-GIMBAL	3	1-AC 641G 2-AC 642G	3	2-GG 177B 1-4310	D	MAGIC 331	CAPT WETTERSTROM	1968	AD395066L	(S)

APPENDIX C CONTINUED

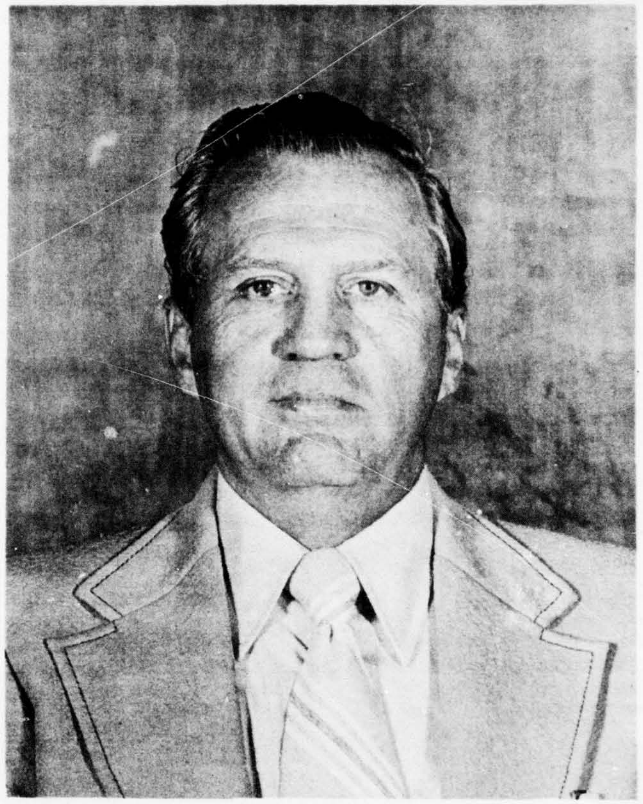
PROGRAM	TYPE OF SYSTEM	SHORT TITLE	TEST CODE	CONTRACTOR	TYPE OF PLATFORM	GYROS NR	GYROS TYPE	ACCELEROMETERS NR	ACCELEROMETERS TYPE	TYPE OF COMPUTER A=Analog D=Digital		TEST ENGINEER	TEST START	DDC ACQ NUMBER	
139A	AMSA-INS	N-16	D	AUTONETICS	3-GIMBAL	2	G-9	3	UM-8	D	MARDAN	CAPT SORENSEN	1968	AD395066L	(S)
139A	AMSA-INS	LCI	D	GPI	4-GIMBAL	3	ALPHA III	1	2414	D	L-90-1C	MR MOYER	1968	"	(S)
69DF	CLOSE AIR SUPPORT SYSTEM	CLASS	D,V	LITTON	4-GIMBAL	2	G-300G2	3	A-200D	D	LC-728	CAPT HACKFORD	1970	AD516783L	(C)
69DF	INERTIAL NAVIGATOR	CAROUSEL IV	V	A-C	4-GIMBAL	3	AC-651G	3	AC-653A	D	MAGIC III	CAPT HEASLEY	1970	AD886564L	(U)
688G	STRAPDOWN KALMAN INERTIAL DOPPLER	SKIDS	V ,D	HONEYWELL	STRAPDOWN	3	GG-334A9	3	DGG-177	D	D201M	CAPT ROSE	1970	AD884579L	(U)
69DF	INERTIAL NAVIGATOR	CAROUSEL VM	V	A-C	4-GIMBAL	3	ZC-651G	3	AC-653A	D	MAGIC III	CAPT HEASLEY	1970	AD886564L	(U)
666A	DOPPLER INERTIAL LORAN	DILS(LN-30)	D	LITTON	4-GIMBAL	2	G-1200	3	A-1000	D	LC-728	MR JOHNSON	1970	AD519289L	(C)
328A	INERTIAL NAVIGATOR	F-15 INS ASN-109	D,V	LITTON	4-GIMBAL	2	G-1200	3	A-1000	D	DDA	CAPT HEASLEY	1971	AD892275L	(U)
666A	GIMBALLED ELECTRO STATIC GYRO INS	GEANS AN/ASN-101	D	HONEYWELL	4-GIMBAL	2	ESG	3	DGG-177	D	DBG 8196A1	LT GNIADY	1971	AD523446L	(C)
666A	INERTIAL NAVIGATOR	LN-12	V	LITTON	4-GIMBAL	2	G-200	3	A-2000	A	ASN 63 ASN 56	LT KING	1971	AD525467L	(U)
688G	INERTIAL NAVIGATOR	INS-61	V	KEARFOTT & COLLINS	4-GIMBAL	2	GYROFLEX KT-7E	2	KEARFOTT 2401	D	DDA	CAPT MOORE	1971	AD900352L	(U)
688G	INERTIAL NAVIGATOR	F-15 INS ASN-109 HELICOPTER	V	LITTON	4-GIMBAL	2	G-1200	3	A-1000	D	DDA	CAPT HEASLEY	1971	AD894139L	(U)
688G	INERTIAL NAVIGATOR	SKN-2400	V	SINGER-KEARFOTT	4-GIMBAL	2	SKG-2900	3	SKA-2900	D	SKC-3000	CAPT KING	1973	ADB005811L	(U)
688G	CIRIS	CAINS	V	LITTON	3-GIMBAL	2	G-300G2	3	A-2000	D	LC 728	CAPT BRINKER MR PEARSON	1973		
666A	GIMBALLED ELECTRO STATIC GYRO INS	GEANS AN/ASN-101	D	HONEYWELL	4-GIMBAL	2	ESG	3	DGG-177	D	HDC-601	CAPT MONTGOMERY	1974	ADC001025	(C)
139A	DOPPLER-INERTIAL NAVIGATION SYSTEM	B-1(LN-15S)	D	BOEING/LITTONS SINGER-KEAR	3 GIMBALL	2	G-300G2	3	A200D	D	SKC-2070	MR PRESTON	1974		
688G	INERTIAL NAVIGATOR	LN-37	V	LITTON	4-GIMBAL	2	G-1200	3	A-1000	D	LC-4516	CAPT King	1974		
666A	INERTIAL NAVIGATOR	N-57A-2	D	AUTONETICS	STRAPDOWN	2	MESG	3	EMA	D	D-216	CAPT PAYNE	1974		
688G	INERTIAL NAVIGATOR	SKN-3000	V*	SINGER-KEARFOTT	STRAPDOWN	2	HYREX II	3	SKA-2900	D	SKC-3000	CAPT RITCHEY	1975		
688G	INERTIAL NAVIGATOR	HSDN-1020	V*	HAMILTON STD	STRAPDOWN	3	RI-1010	3	SUNDSTRAND Q-FLEX	D	AIDS	LT HAAS	1975		

APPENDIX C CONTINUED

PRO GRAM	TYPE OF SYSTEM	SHORT TITLE	TEST CODE	CONTRACTOR	TYPE OF PLATFORM	GYROS NR	GYROS TYPE	ACCELEROMETERS NR	ACCELEROMETERS TYPE	TYPE OF COMPUTER A=ANALOG	TYPE OF COMPUTER D=DIGITAL	TEST ENGINEER	TEST START	DDC ACQ NUMBER
688G	INERTIAL NAVIGATOR	LN-40	V*	LITTON	4-GIMBAL	2	G-4	2	A-4	D	LC-516	LT HAAS	1975	
688G	INERTIAL NAVIGATOR	LTN-72	V	LITTON	4-GIMBAL	2	G-2	3	A-2	D	C-4000	LT HAAS	1975	
666A	INERTIAL NAVIGATOR	LINS	D	HONEYWELL	STRAPDOWN	3	LASER GG1300AB04	3	SYS-DON 4841F-10	D	HDC-301A	CAPT PAYNE	1975	
670B	MISSILE INERTIAL NAVIGATOR	RACG	D*	SPERRY	STRAPDOWN	3	LASER 8000 SERIES	3	SUNDSTRAND Q-FLEX	D	DELCO MAGIC 362	CAPT RITCHEY	1975	

BRIEFING TITLE

PERSHING INERTIAL SYSTEM LIFE EXTENSION AND ASSESSMENT PROGRAM



JAMES V. JOHNSTON

James V. Johnston is presently an Aerospace Research Engineer in the Inertial Systems Development Group of the Guidance and Control Directorate of the Army Missile Command. Mr Johnston has been involved in research and development of inertial hardware for the Army since 1955. He worked alongside the original German Team from Peenemunde on developing the Redstone and Jupiter Missile Inertial Guidance Equipment. He holds 21 patents on guidance systems and components. He has received both the Army Certificate of Achievement and the Army Engineering and Scientific Achievement Awards.

PERSHING LIFE EXTENSION ASSESSMENT PROGRAM

JAMES V. JOHNSTON
GUIDANCE & CONTROL DIRECTORATE
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US ARMY MISSILE COMMAND

The PERSHING missile stockpile has exceeded its 10 year useful service life. In a combined effort to save cost, continue to assure long range strike capability and provide uninterrupted service, the Army initiated a Life Extension Assessment Program (LEAP). The objective of this program was to determine any age related degradation or wear and tear on the inertial system and to recommend actions to extend the life of the existing PERSHING stockpile.

To enhance the success of the task, the program was divided into three phases:

Phase I was the planning and development of test criteria. Structuring of rationale for fault determination of incoming material. System and component non-destructive and diagnostic test plans along with special inspection techniques.

Phase II was the missile G&C section sampling assessment program. This phase included the selection process, the inspection, test and hardware assessment. Disassembly of parts evaluation and reassembly. Data assessment, preliminary report of findings and remanufacture recommendations program.

Phase III was the remanufacture phase based on the findings of Phase II. The recommendations were incorporated with the end result of a homogeneous stockpile of new and remanufactured inertial systems capable of operational use into the 1980's.

The major problem facing the assessment program was the ability to select a representative quantity of inertial systems that would depict the true condition of fielded systems. Table 1 shows a summary of the sample selections. Additionally, the selection would have to come from fielded spares without interrupting or jeopardizing the quantity of missiles on ready status. It was further decided that the assessment should be done outside Army maintenance and repair channels so that these facilities would not become overcrowded. The Navigation and Control Division of Bendix, the original manufacturer of the ST-120, was contracted with to perform the test and assessment program.

After some deliberation, a hardware quantity of ten (10) ST-120 platforms and servo amplifiers was selected to meet the minimum operational impact and cross section of the quality in the remaining fielded systems. With this small a sample size, tight conditions were placed on the inertial systems to be examined. Figure 1 shows an ST-120 platform with the cover removed.

ST-120 SUBSYSTEM STATISTICS

SUBSYSTEM NUMBER	PLATFORM S/N	PLATFORM RUN TIME	PLATFORM CALENDAR LIFE	SERVO AMPLIFIER S/N	SERVO AMPLIFIER RUN TIME	SERVO AMPLIFIER CALENDAR LIFE
*1	430	127	5 Yr/5 Mo	498	126	5 Yr/5 Mo
2	503	411	5 Yr/1 Mo	371	446	6 Yr/4 Mo
*3	154	571	7 Yr/2 Mo	229	600	7 Yr/2 Mo
4	383	482	5 Yr/11 Mo	396	110	6 Yr/2 Mo
5	195	500	7 Yr	375	552	6 Yr/6 Mo
*6	111	392	8 Yr	185	510	8 Yr
*7	437	388	5 Yr/9 Mo	510	397	5 Yr/9 Mo
8	208	403	7 Yr/1 Mo	391	279	6 Yr/8 Mo
*9	223	300	7 Yr/2 Mo	290	275	7 Yr/2 Mo
10	603	736	4 Yr/7 Mo	682	812	4 Yr/6 Mo

* Original MATCHED Subsystem

TABLE 1

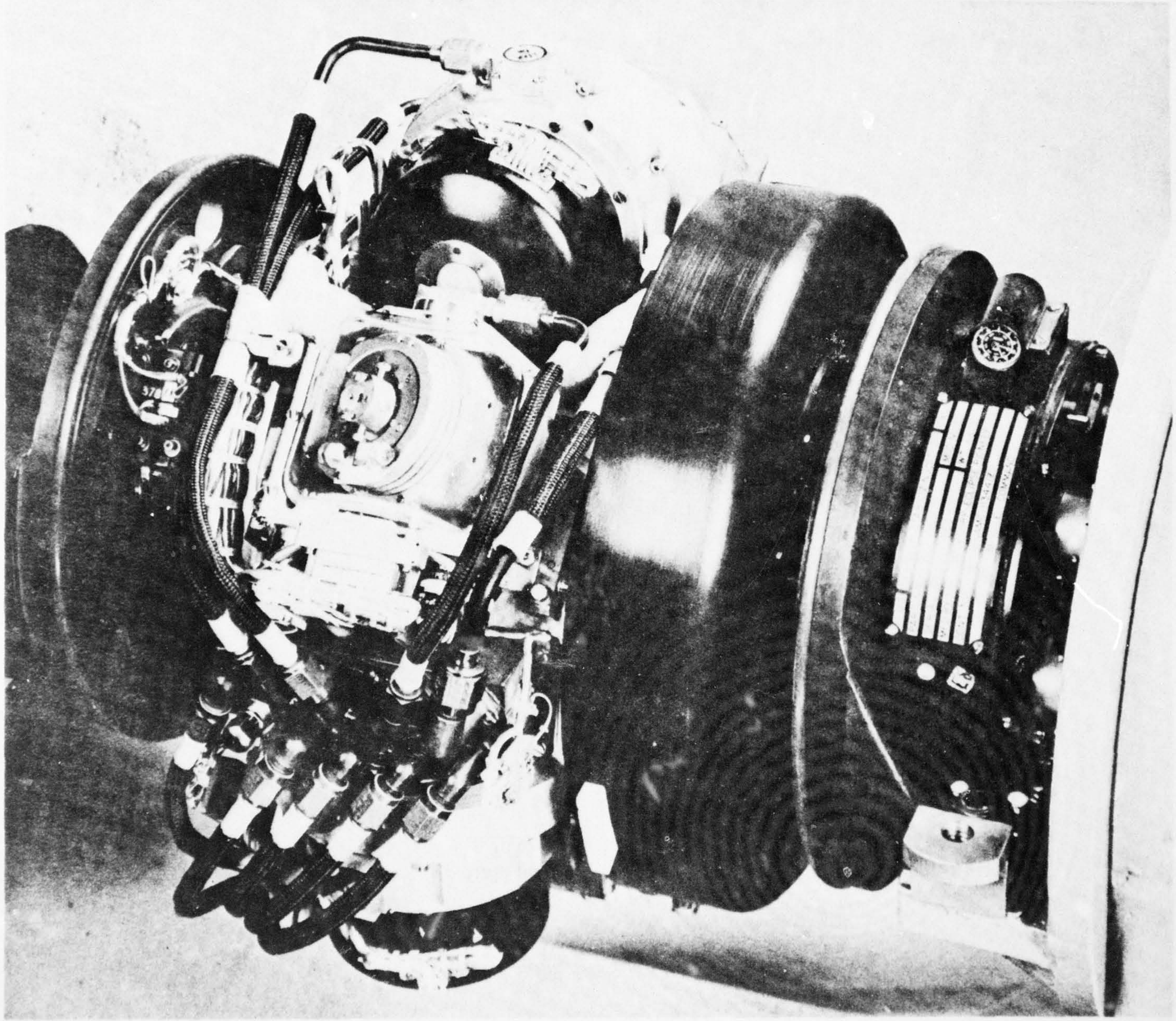


FIGURE 1

ST-120 PERSHING STABLE PLATFORM

The platforms for assessment should be fully operational, free of major or catastrophic defects, in excess of five (5) year calendar life and actual operating time in excess of 1000 hours. To preclude any unusual situations involving hardware condition as received or any failure in the subsequent tear down a hardware contingency plan was set up for long lead items. Table 2 depicts the component size and compares with MIL STD for assessment sample.

The first step in the assessment process was to perform a complete incoming inspection test identical to the original manufacturing test. Complete traceability of each system and component was available. Therefore, starting from this point, degradation could be determined based on field operating and handling procedures.

After completion of the system test, selected subassembly tests on most items was conducted. These tests provided data on specific subassemblies which were subject to wear and age degradation. Such assemblies as the gyros, pendulous integrating accelerometers, and gimbal gear packages fit the criteria of subassemblies.

In order to establish an accurate casual relationship between component performance degradation and the age or wearout susceptibility of the component, a diagnostic evaluation was performed entailing, where necessary, the destruction of the particular component or assembly. The inertial components were disassembled to enable test of the pickoff, torquer assemblies, inspection and test of inner cylinders, spin motor test, synchro electrical tests, etc. Electromechanical assemblies such as motors and synchros were disassembled to evaluate the effects of age and wear on brush contacts, lamination stacks, lead anchorage, condition of insulation, etc.

Servo amplifier cards had their ruggedizing compound removed. The electrical components were subjected to tests to determine the effect of age on the individual component parameters. Semiconductors, transformers, resistors, capacitors, and reactors were tested to determine any variance from the original drawing requirements.

The detailed assessment tests included a comprehensive visual inspection of the sealed ST-120 platform which covered:

1. Warped covers causing improper seal.

2. Connector pin and insert for general wear.

3. Bent pins on connectors.

4. Air fittings for proper seal.

5. Window of platform for scratches, cracks, discoloration.

SUMMARY OF SAMPLE SELECTIONS

	MFR	MIL-STD-414 SAMPLE SIZE	% POPULATION	MICOM SAMPLE	% POPULATION	DISASS'Y SAMPLES	% SAMPLE	DIAGNOSTIC EVALUATION	% SAMPLE
PLATFORM	696	30	4.3	10	1.4	10	100	--	--
GYROS	2100	40	1.9	30	1.4	15	50	7	23
ACCEL.	2100	40	1.9	30	1.4	15	50	7	23
GEAR ASSY	2100	40	1.9	30	1.4	30	100	--	--
PENDULUM	1400	40	2.9	20	1.4	4	20	4	20
SERVO AMP	696	30	4.3	10	1.4	10	100	--	--
GYRO CARDS	2100	40	1.9	30	1.4	10	33	10	33
ACCEL CARDS	2100	40	1.9	30	1.4	9	30	9	30

TABLE 2

4. Solder joints.

5. Condition of lead wires.

The identical procedure was used on control transformers. Other subcomponents such as resolvers, caging gearhead and motor, leveling pendulum, and wiring harness were inspected to the same degree of thoroughness. Figure 2 shows a typical gear package assembly.

The AB-5 gyros were subjected to the original calibration test. Here again, comparison was made with original data. Special attention was given to wheel spinup and coast down time as well as power requirements. These types of tests would signify wear and loss of lubrication on the spin bearings. Fifteen (15) of the thirty (30) units were selected for further investigation. These units were disassembled down to the inner float assembly. The pickoffs and torquers were spearately tested. Leak tests were made on all float assemblies. Finally, seven (7) of these inner cylinders were disassembled and tests made on the gyro spin motor. These tests included:

1. Preload measurements.

2. Dynamic unbalance.

3. Bearing noise.

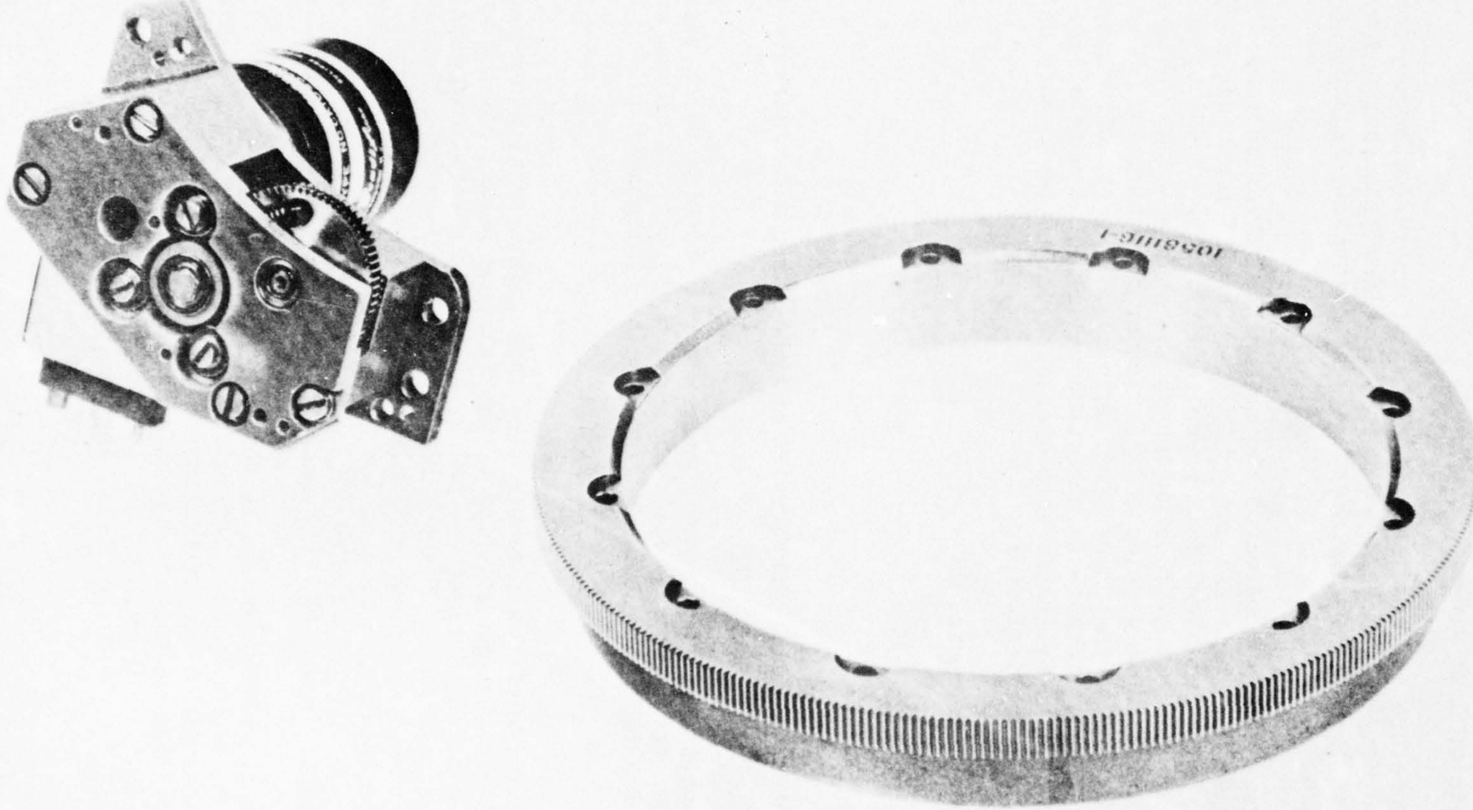
The gyro spin notor was then disassembled and the parts dimensionally and electrically checked.

The pendulous integrating accelerometers were subjected to an identical evaluation as were the gyros. Additional investigative tests on the accelerometers included scale factors, side balance and base alignment.

ASSESSMENT

At the completion of the investigative phase, data results were assembled and reviewed. Analyzing and grouping of the failures began to provide patterns which were attributable to run time, aging, and environmental exposure. To assist in further definition of the failures, all previous test and repair data sheets of the platform and servo amplifier were compiled and analyzed. The Army utilized the Bendix Corporation for maintenance and repair when the PERSHING system was fielded in June 1963, until a repair facility was set up at Pueblo Army Depot in Jan 67. A summary of this data is contained in Table 3.

Rather than expose the reader to the actual volumes of data obtained at system, subsystem, and component level, it is more indicative of the techniques used to follow through on one typical subcomponent. The Pitch Control Transformer provides a representative component with mechanical and electrical characteristics. Figure 3 is a photograph of a Pitch CT. Following the outline procedures, the initial test was the visual inspection of the 10 Pitch CT's. The

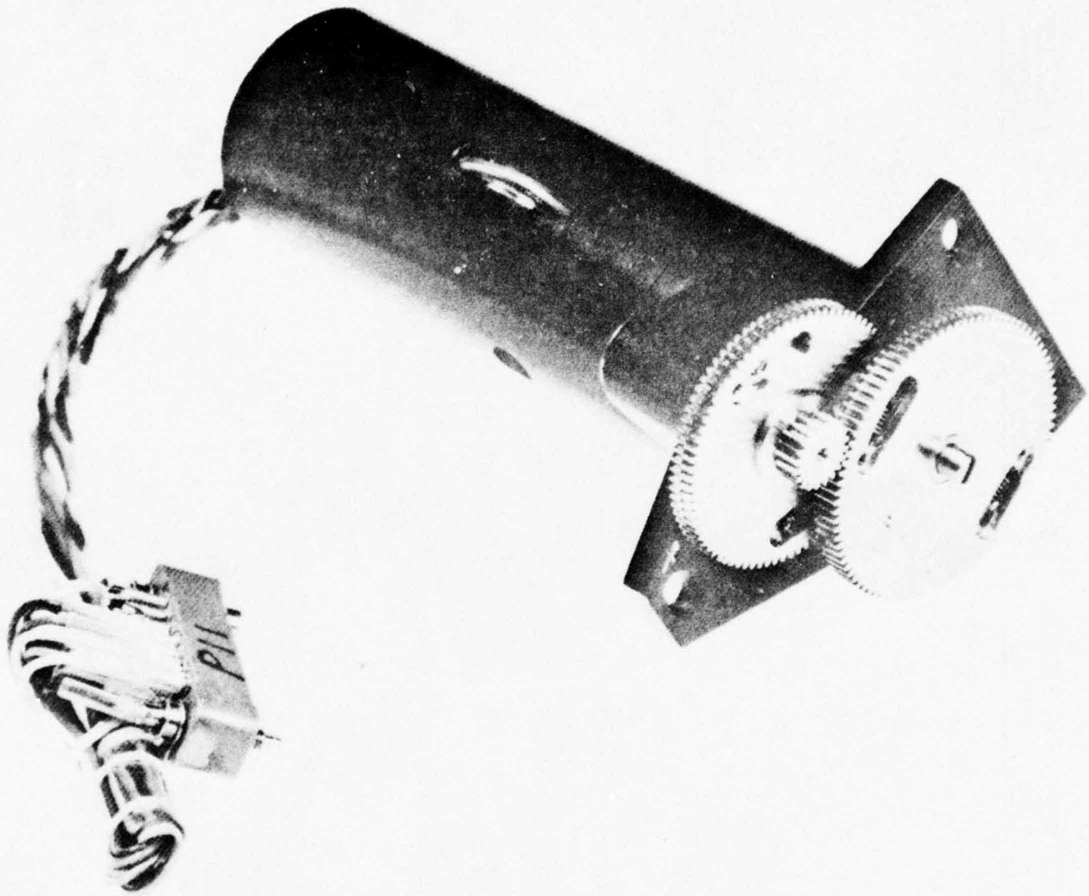


PITCH, CONNECTOR AND GEAR HOUSING ASSEMBLY
AND PITCH RING GEAR

FIGURE 2

	BENDIX 7/63 THROUGH 9/70		PUEBLO 1/67 THROUGH 9/70	
PLATFORM	REPORTED FAILURES / MODULES TESTED	% OF MODULES TESTED	REPORTED FAILURES / MODULES TESTED	% OF MODULES TESTED
STABILIZING GYRO X, Y, Z	53/384	13.8	25/1143	2.1
ACCELEROMETER CR, SR, SA	71/384	18.5	60/1143	5.2
PENDULUM X, Z	30/256	11.7	51/762	6.7
GEAR PACKAGE P, R, Y	39/384	10.2	48/1143	4.2
NULL ADJ ASS'Y	10/128	7.8	150/381	39.3
MICROSYN X, Y	13/256	5.1	10/762	1.3
PITCH CT & RESOLVER ASS'Y	7/128	5.5	37/381	9.7
PITCH GEAR/BEARING	4/128	3.1	48/381	12.6
CAGING MOTOR ASS'Y	12/128	9.4	31/381	8.1
PRISM	3/128	2.3	35/381	9.1
SERVO AMPLIFIER				
Z LOOP AMP	2/88	2.3	26/381	6.8
X. Y LOOP AMP	9/176	5.1	36/762	4.7
ACCEL AMP	14/264	5.3	85/1143	7.4
	128 Platforms & 88 Servo Amp		381 Platforms & Servo Amp Systems	

TABLE 3



SYNCHRO AND CONNECTOR ASSEMBLY
(PITCH/RESOLVER ASSEMBLY)

6. Screws and thread wear due to extensive cover removal.

7. Frame and surface damage, point chip, rust, etc.

The visual inspection of the servo amplifier covered:

1. Physical damage.

2. Dirt, rust, pitting, etc.

3. Loose connectors on cards.

4. General condition of the cards.

   a. Ruggedization condition.

   b. Burnt or discolored components.

   c. Warped cables.

   d. Connector pin condition.

When the platform covers were removed, detailed visual inspection of the platform covered:

1. Prism for scratches and discoloration.

2. Discoloration of accelerometer covers.

3. Physical damage.

4. Harness insulation and general condition.

5. Caging cone wear and "O" ring wear.

6. Dirt and contamination.

7. Fabric covering on air line hoses.

8. Heater insulation deterioration.

The platform was then subjected to a detailed system test to compare with the original test data. This comparison provided the tolerance changes from original manufacture. The evaluation of this data was oriented towards analyzing those conditions which were believed to arise from aging or wear of components.

Detail mechanical investigation was conducted on subcomponent parts of the platform. Such components as the gimbal microsyns were first subjected to a thorough visual, electrical and mechanical test. Again, the data was compared with original manufacturer records to evaluate effects of age and wear. Three (3) of the twenty (20) microsyns were totally disassembled to further evaluate aging effects. Portions of the molding material were cut out for chemical evaluation. The remaining molding material was chemically removed to allow assessment of age effects on the four coils and lamination stack. Wiring was checked for proper anchorage and insulation degradation.

Gear housing assemblies, as shown in Figure 2, were removed and totally checked at the assembly and subassembly level. In addition to performance determination, each gear, shaft, and bearing were examined for:

1. Dirt accumulation.

2. Gear profile.

3. Nicked teech.

4. Smoothness of rotation.

5. Loose screws.

6. Bearing friction.

The servo motors were tested against the original procurement specification. In addition to all of the normal performance tests, three (3) of the servo motors were disected and each subassembly was subjected to the following mechanical checks:

1. Fit between bearing bore and the rotor assembly journal.

2. Fit between the bearing O.D. and the housing stator assembly bore.

3. Limits of rotor shaft end play with a one pound gauging load.

4. Radial play of the rotor shaft in the motor.

5. Rotor shaft runout.

The stator assembly was checked for:

1. Loose wires.

2. Scraped or nicked inpregnation or insulation on end turns.

3. Flaking of varnish or loose material on assembly.

assemblies indicated no major age related or wearout problems. The second test involved electrical measurements which are listed in Tables 4 and 5. The electrical data is also summarized in the graph shown in Figure 4, along with the original test data obtained when the system was initially fabricated. Upon completion of the electrical tests, a series of mechanical tests and measurements were then made. These results are summarized in Table 6. An individual piece part inspection of the disassembled Pitch CT was then conducted. Visual inspection disclosed no evidence of any dirt accumulation, nicked gear teeth, surface discoloration, surface wear or physical damage on any piece part. A diagnostic evaluation was then conducted on two of the 10 Pitch CT's.

<u>Pitch CT S/N 195</u>

Functional Tests - No deviations, assembly acceptable.

Bearing Evaluation - Extreme loss of lubricant in all ball bearings.

Slip Ring Evaluation - Examination revealed very little surface wear .53% max.

<u>Visual Inspection</u>

Rotor Assembly - Score marks on shaft caused by collar clamps (cosmetic defect)

Stator Assembly - No sign of wear.

<u>Pitch CT S/N 603</u>

Functional Test - Rotor phase open, assembly not functional (cause unknown)

Bearing Evaluation - Extreme loss of lubricant in all ball bearings.

Slip Ring Evaluation - Examination revealed very little surface wear 1.2% max.

<u>Visual Inspection</u>

Rotor Assembly - Magnetic wire near slip rings show signs of abrasion - one wire severed.

Stator Assembly - No apparent signs of wear.

<u>ANALYSIS</u>

1. Except for the extreme loss of lubricant in all ball bearings due to migration and evaporation with time and one functional failure, no major wear and tear, age, or nonage related defects were encountered.

SUMMARY OF ELECTRICAL MEASUREMENTS

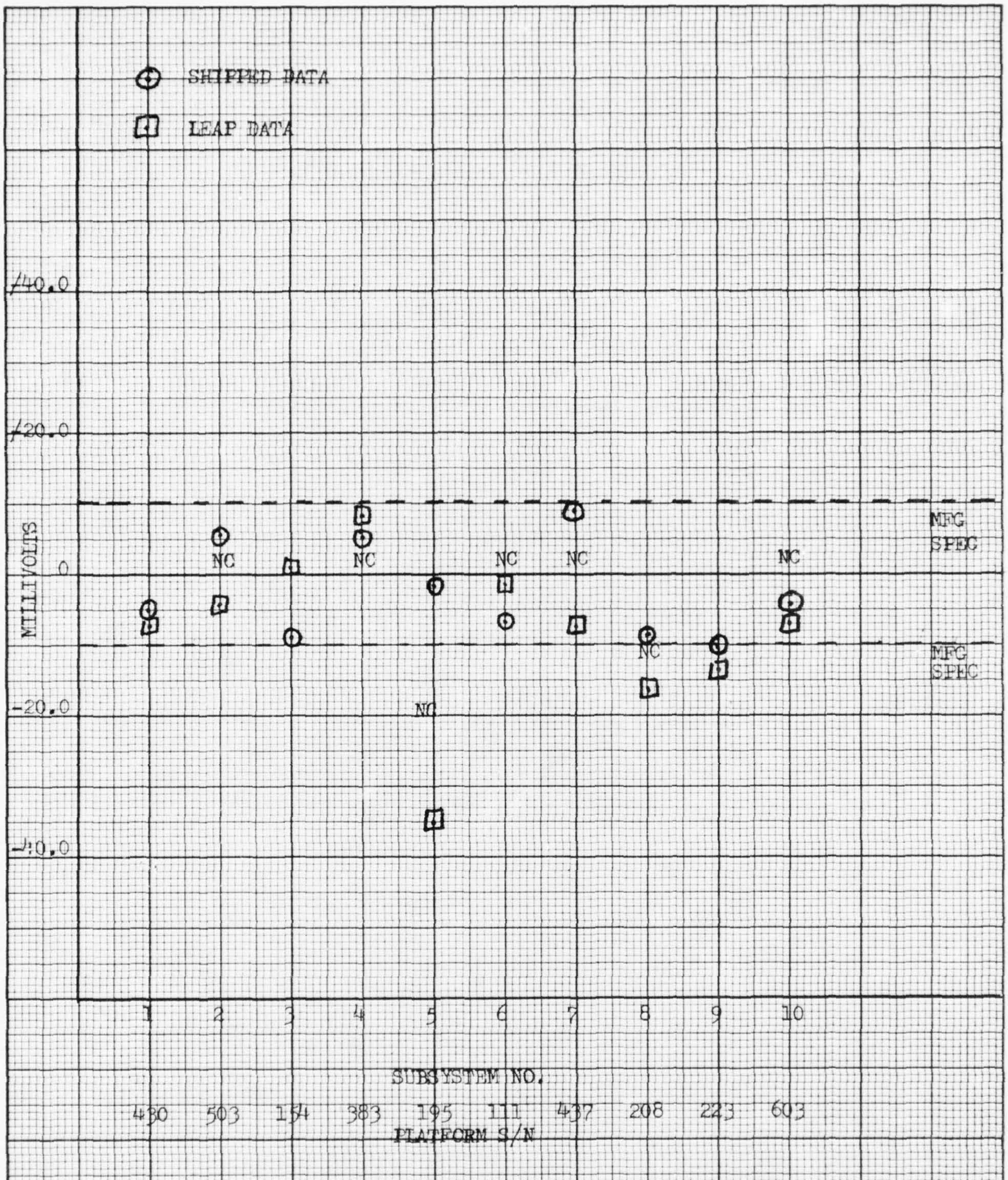
ST-120 PLATFORM SN		154	195	383	430	503
INSULATION BREAKDOWN		OK	OK	OK	OK	OK
INSULATION RESIS SPEC = 100 MEG MIN		100>	100>	100>	100>	100>
ROTOR DC RESISTANCE & BRUSH CONTACT	Winding Spec 180-132 Ω	126.8	120.8	121.7	123.7	119.6
	8 RPM Spec .5 Ω	.15	.10	.05	.10	.05
	166 RPM Spec .5 Ω	.25	.15	.10	.05	.2
STATOR DC RESISTANCE WINDINGS	Lead #1 Spec 14.4-17.6 Ω	17.0	10.4	17.1	16.8	16.7
	Lead #2 Spec 14.4-17.6 Ω	17.0	16.4	17.0	16.8	16.8
	Lead #3 Spec 14.4-17.6 Ω	17.0	16.4	17.0	16.8	16.8
0°	Fundamental Spec 20 MV MAX	9	7	1	5	14
	Total Spec 40 MV	10	24	4	6	16
180°	Fundamental Spec 20 MV MAX	5	8	9.4	5.4	17
	Total Spec 40 MV MAX	7	24	13.0	5.2	19

TABLE 4

SUMMARY OF ELECTRICAL MEASUREMENTS

ST-120 PLATFORM		154	195	383	430	503
CALIB. & PHASE ROTATION SPEC = ≮ 10 MIN		+6	-9	-9	+7	+9
ROTOR OUTPUT & PHASE SHIFT	Ratio Spec 2.12 - 2.29	2.17	2.24	2.17	2.185	2.18
	Phase Shift 7.5^{o}-11.5^{o}	9.6^{o}	10.4^{o}	10.0^{o}	9.4^{o}	9.5^{o}
STATOR IMPEDANCE	16.15 - 21.85	18.0	17.5	20	18	17.5
	J65.7 J80.3	72.8	79.3	71.5	77.8	71.6

TABLE 5



PITCH C.T. NULL-IN-PHASE

FIGURE 4

SUMMARY OF MECHANICAL MEASUREMENTS

ST-120 PLATFORM	154	195	383	430	503
END PLAY Spec .002 - .0012	.0006	.0007	.0009	.001	.0009
FRONT SHAFT Spec .001 MAX	.0004	.0005	.0008	.0004	.0005
REAR SHAFT Spec .001 MAX	.0002	.0004	.0007	.0004	.0003
FRICTION Spec 3 GM - CM MAX	<3	<3	<3	<3	<3

TABLE 6

2. The useful life of the Pitch CT assemblies can, therefore, be projected through 1980 by implementation of a remanufacture plan to cover the problems found above. Additionally, the results of the field performance and maintenance histories were included to provide a more comprehensive picture.

(62) Reported rejections at PUAD (1/67 - 5/71).

60 CT nulls out of spec, were adjusted

1 Pitch CT gear defective - replaced.

1 Burr on Pitch CT idler gear - removed burr

(3) Pitch CT anomalies - BDX (1/63 - 5/71).

1 CT null out of spec - adjusted.

1 CT unserviceable - replaced

1 CT out of spec at 2° - not verified.

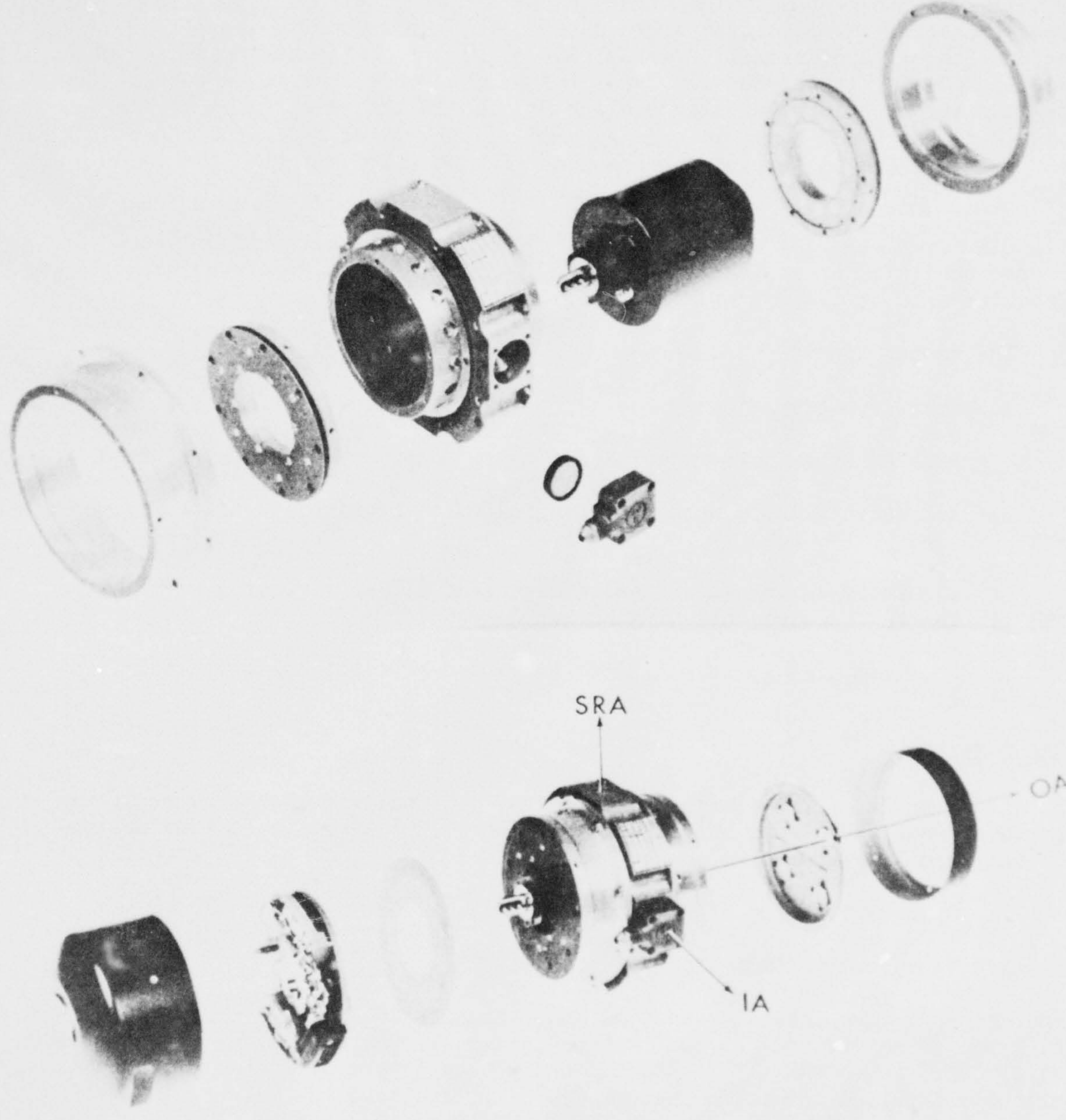
With this input data and findings, the recommended steps to be applied to the Pitch CT of the ST-120 stockpile were:

- Remove from platform
- Disassemble and clean
- Replace or refurbish all ball bearings (6)
- Replace defective worn brush block assemblies and rotors as required.
- Reassemble and test to subassembly level

Cost tradeoffs:

- Replace with new unit $749.76
- Remanufacture $329.36

The AB-5 gyros offered a more interesting and challenging analysis. Thirty (30) of these platform components were examined. Figure 5 shows an exploded view of an AB-5 gyro. Based on performance results, 15 of these units were selected for disassembly. Eleven (11) to the inner float assembly and four (4) to the motor level. All disassembled parts were visually, mechanically, and electrically inspected where applicable to determine if any defects existed on air bearing component geometry or surfaces; also to determine if any degradation



AB-5 GYROSCOPE ASSEMBLY

FIGURE 5

of wiring insulation, wear of moving parts, changes in gyro motor torque, corrosion, or deterioration of bearing lubricant existed. Table 7 is a list of the major parameters that were out of specification or failed. Correlation of failures with causes could then be ascertained. The four (4) gyros showing excess constant error torque were subjected to an air bearing inspection. The results of this inspection revealed two (2) gyros were contaminated and one (1) had air bearing damage. Four (4) of the gyros exhibiting out of spec conditions on mass unbalance along SA also indicated the mass unbalance value was unstable. Further tear down and investigation indicated the unstable condition was due to bearing lubrication failures which affected the gyro wheel preload.

Electrical testing of all pickoffs and torquers resulted in only one out of spec condition of a pickoff trim pot. This required a simple adjustment not effecting unit or platform performance.

The major defects found were:

1. Beryllium corrosion on the three (3) gyros from platform 154.

2. All "O" rings were rejected for being compressed and contaminated.

3. All inlet filters were contaminated which required cleaning or replacement.

4. Eight (8) AN connectors had evidence of silver migration through the gold plating and required cleaning or replacement.

5. Fourteen (14) gyros exhibited varying degrees of silver sulfide contamination.

GYRO SUMMARY

As a result of the testing, inspection, and analysis of the gyro, it was concluded that there were no critical problems. The significant findings resulting from LEAP are as follows:

1. Gryo drfit degradation (major defect).

2. Flex lead contamination (major defect).

Regarding the gyro drift degradation and referring to Table 7, there were six (6) gyros of thirty (30) tested that exhibited excessive constant torque. Seven (7) gyros of seventeen (17) inspected had a high degree of contaminates which seriously impaired the performance reliability and have the potential of air bearing failure. This amounts to 41% of the gyros disassembled.

Sixteen (16) of the thirty (30) units tested had excessive mass unbalance torque along the SA. Four (4) of the sixteen (16) also exhibited excessive

AB-5 GYRO TEST/INSPECTION FAILURES

PLATFORM S/N	430	503	154	383	195	111	437	208	223	603	TOTAL
EXCESS MASS UNBALANCE ALONG SA	2	2	2	2		1	2	2	2	1	16
EXCESS MASS UNBALANCE ALONG IA		1	2	2			1				6
EXCESS CONSTANT TORQUE			2		2			1	1		6
SILVER MIGRATION CONNECTOR	1		1								2
SILVER MIGRATION FLEX LEAD		2	2	2	1	1	1	2	2	1	14
MOTOR BEARING WEAR & OIL BREAKDOWN		1						2	1		4
NOISY MOTOR			3								3
CORROSION ON CYLINDER			3								3
CORROSION ON AIR INLET FILTER			1								1
UNIT CONTAMINATED				1							1
AIR BEARING PARTS SCORED AND CONTAMINATED					1			1			2

TABLE 7

motor bearing torque on the Dynamics Research Corp torque tester. One of these four units was torn down to the motor. Inspection of the motor bearings confirmed the previous indications, from the drift and torque tests, that a lubrication breakdown existed. The mass unbalance along the SA is one of the most critical of the gyro drift terms since one of the possible causes is the aforementioned gyro motor bearing lubrication failure.

The graph of Figure 6 shows that the average mass unbalance term increases with usage. If the specification limit of $.2^{\circ}$/hr is doubled and the resulting $.4^{\circ}$/hr is taken as the point where this parameter requires attention, then Figure 6 indicates this occurs after 1000 hours of run time. Based on the average run time of 770 hours over an average unit age of 6.8 years for the assessment units, this results in a remaining useful life of slightly over two years for the thirty (30) samples.

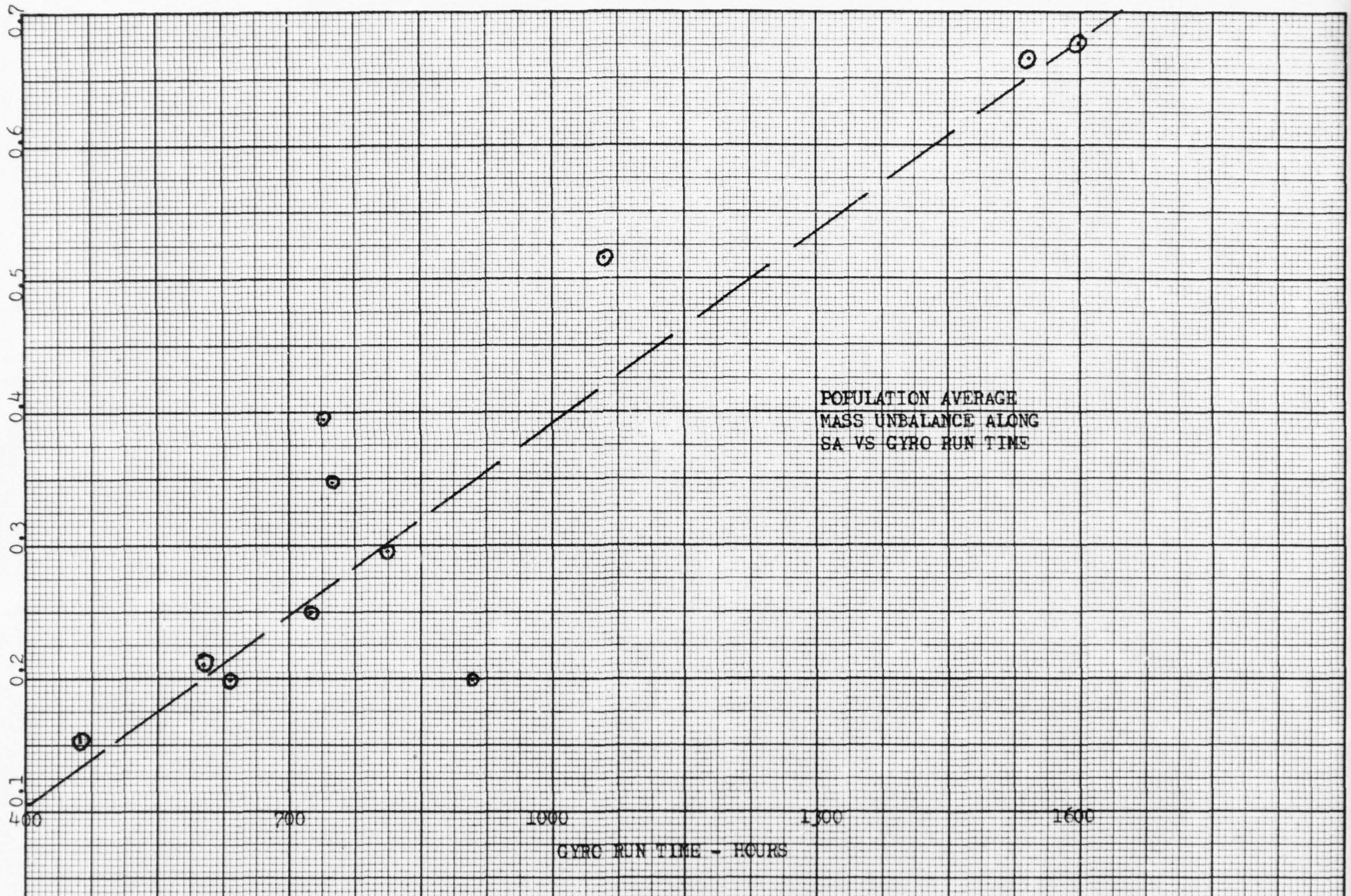
Statistically, five inner cylinder assemblies of fifteen tested, 33% would require replacement to meet LEAP objectives. On the basis of the limited LEAP sampling, it is concluded that this 33% is representative of gyro motor degradation in the field population.

Regarding the flex lead contamination shown in Figure 7, fourteen (14) of seventeen (17) LEAP gyros were found to have sulfide contaminants which definitely can lead to gyro and mission failure. Because the purity of the air supply is highly suspect and unknown at this time, it can only be concluded that any gyro in the field for five years has a 75% chance of being contaminated.

In all other areas, where an age or usage trend is not indicated, the statistical results of the LEAP sampling are considered representative of the field population. The result of the above findings lead to the recommendation of a plan to be applied to all gyros in the ST-120 stockpile.

- Remove from platform and perform drift test and motor run-up.
- Disassemble to the air bearing inner cylinder.
- Perform DRC test.
- Replace defective pickoffs and torquers.
- Replace all flex leads with new material.
- Relap and reassemble inner cylinders that pass the DRC test.
- Complete tests to original manufacture level.

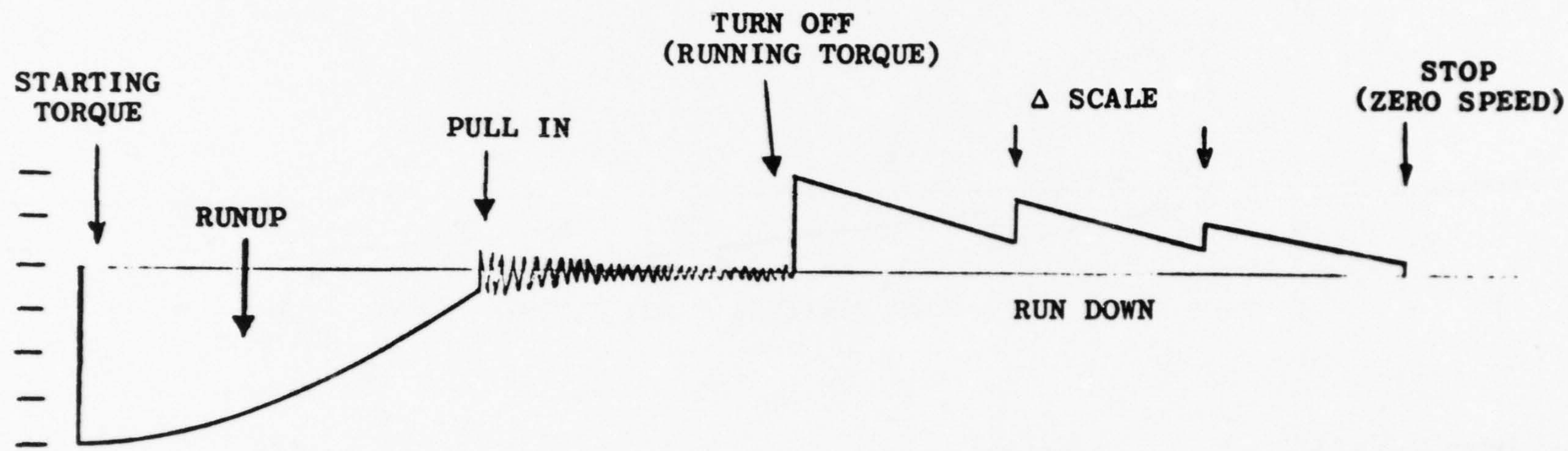
Typical tests with the DRC method of measuring gyro spin motor torque is shown



POPULATION AVERAGE
MASS UNBALANCE ALONG
SA VS GYRO RUN TIME
O/HR
0.1
0.2
0.3
0.4
0.5
0.6
0.7
400
700
1000
1300
1600
GYRO RUN TIME - HOURS

FIGURE 6

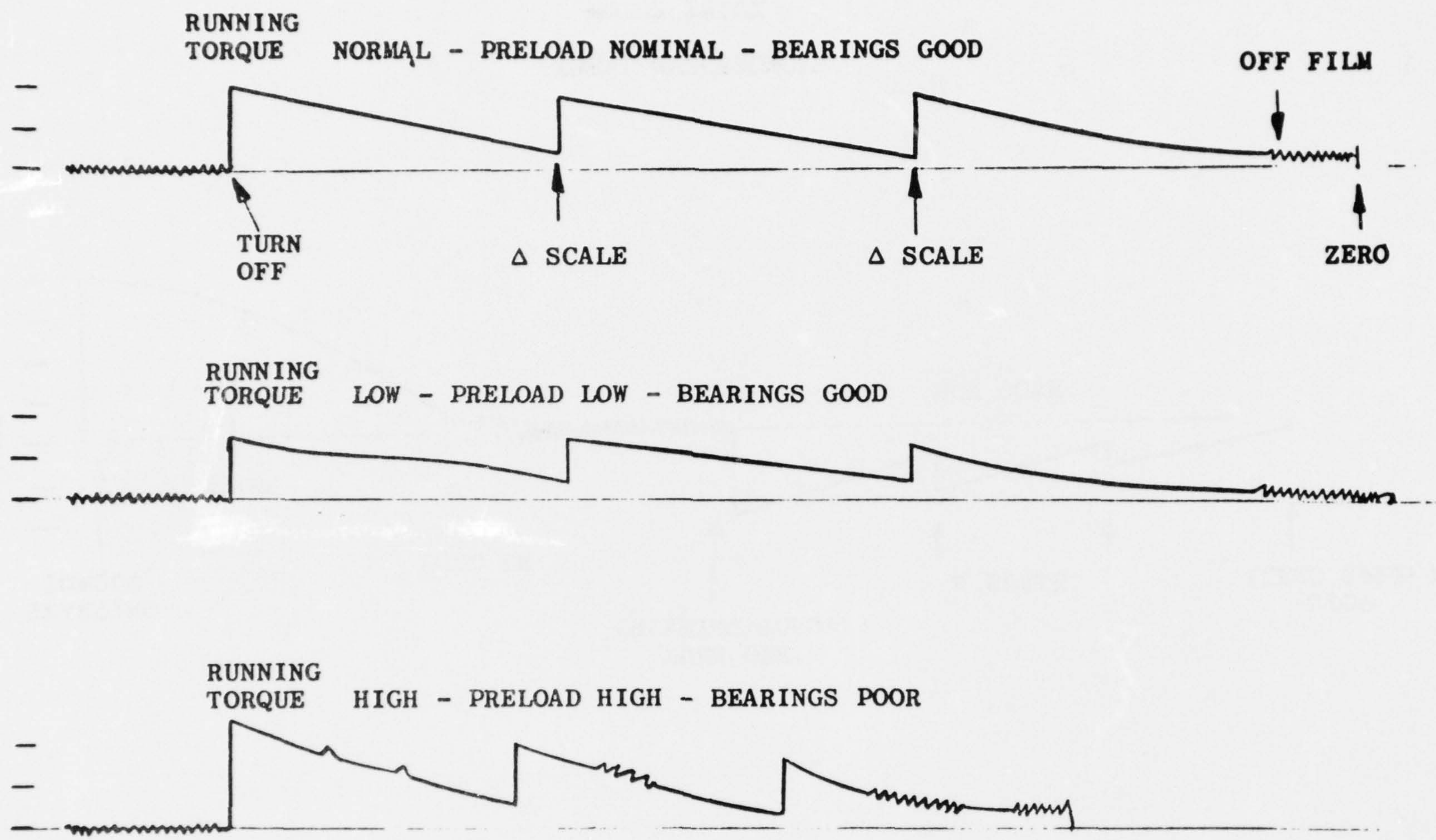
FIGURE 7



IDEAL SYNCHRONOUS

MOTOR TRACE

FIGURE 8



RUNNING TORQUE NORMAL - PRELOAD NOMINAL - BEARINGS GOOD
OFF FILM
TURN OFF
Δ SCALE
Δ SCALE
ZERO
RUNNING TORQUE LOW - PRELOAD LOW - BEARINGS GOOD
RUNNING TORQUE HIGH - PRELOAD HIGH - BEARINGS POOR

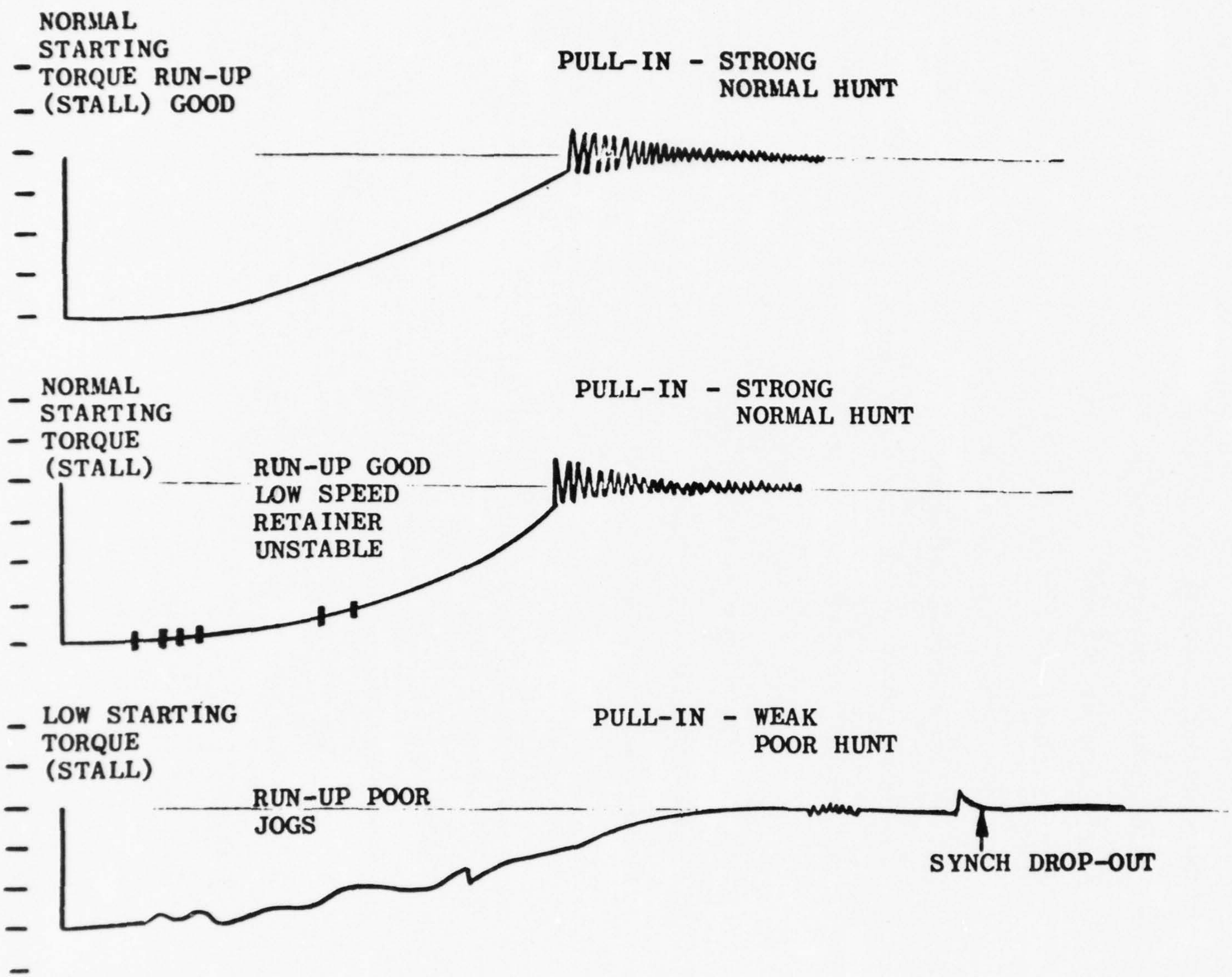

NORMAL STARTING TORQUE (STALL)
RUN-UP GOOD
PULL-IN - STRONG
NORMAL HUNT
NORMAL STARTING TORQUE (STALL)
RUN-UP GOOD
LOW SPEED RETAINER UNSTABLE
PULL-IN - STRONG
NORMAL HUNT
LOW STARTING TORQUE (STALL)
RUN-UP POOR
JOGS
PULL-IN - WEAK
POOR HUNT
SYNCH DROP-OUT

FIGURE 10

in Figures 8, 9, and 10.

Although this paper only discusses two subcomponents of the ST-120 platform, each component was individually examined, tested, and analyzed in a similar manner. The summary results of the mechanical assemblies were:

1. Hardware showing affects of age/usage.

   - Caging mechanism rollers deteriorated as shown in Figure 11.
   - Loss of bearing lubricant.
   - Gasket material degradation.
   - Caging microswitch actuation degradation.
   - Minor evidence of handling/service damage.
   - No serious evidence of gear wear and alignment surface degradation.

2. Hardware showing effects of environmental exposure.

   - Yaw and pitch gimbal bearing corrosion.
   - Main shaft corrosion as shown in Figures 12 and 13.
   - Prism mounting base corrosion.
   - Flex lead silver migration.

The servo amplifier was evaluated in much the same manner as the platform. Figure 14 is a photograph of a servo amplifier. The first test consisted of a functional electrical test with its associated platform in order to establish a comparison with initial "as shipped data". The functional test was followed by a thorough visual inspection which covered:

- Physical damage.
- Loose connectors.
- Ruggedization condition.
- Burnt or discolored components.
- Warped cards.
- Connector pin condition.
- Harness insulation condition.

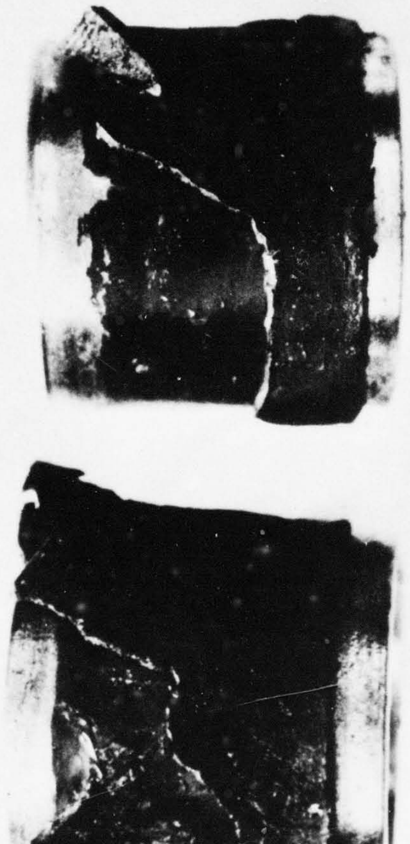


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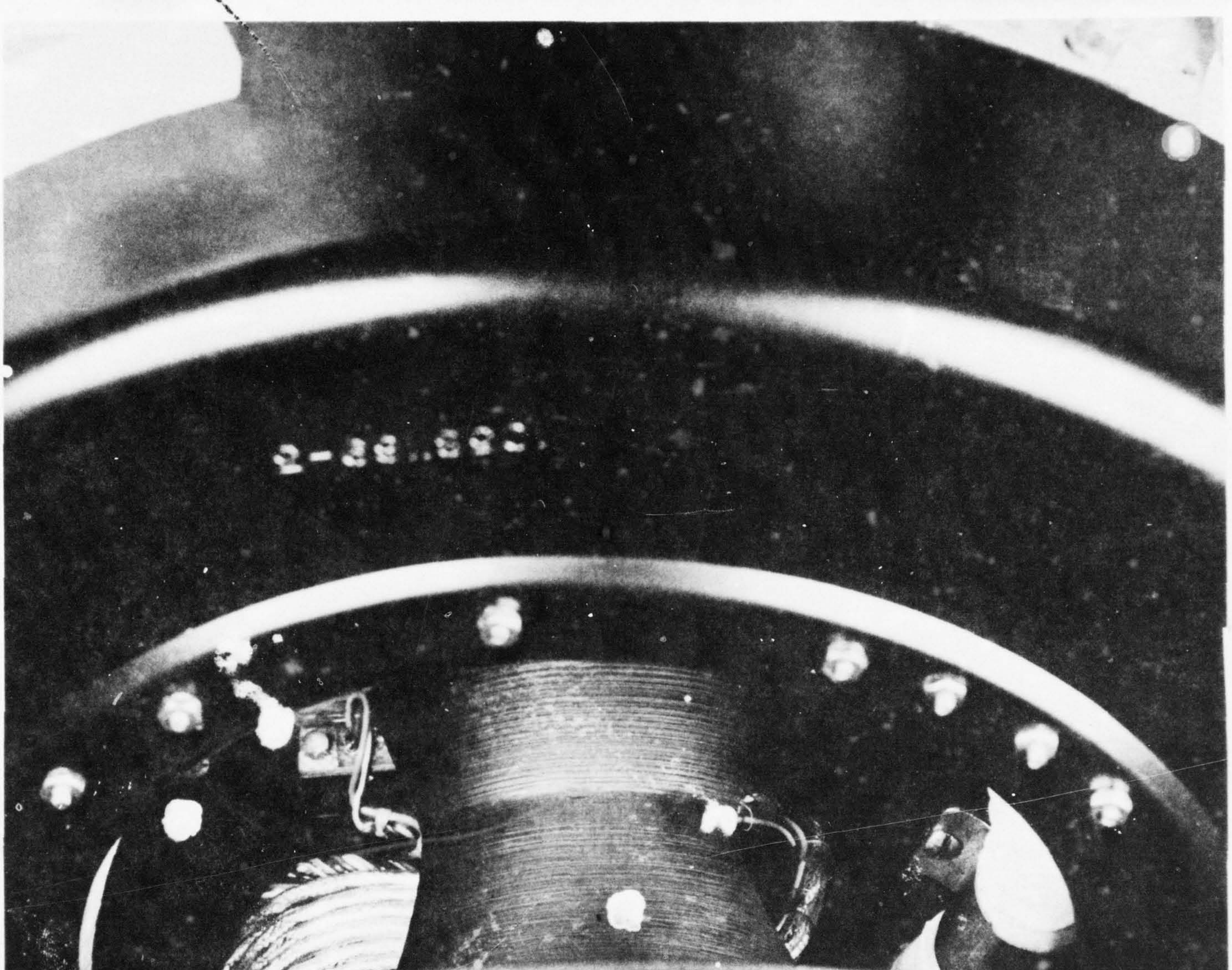
FIGURE 11



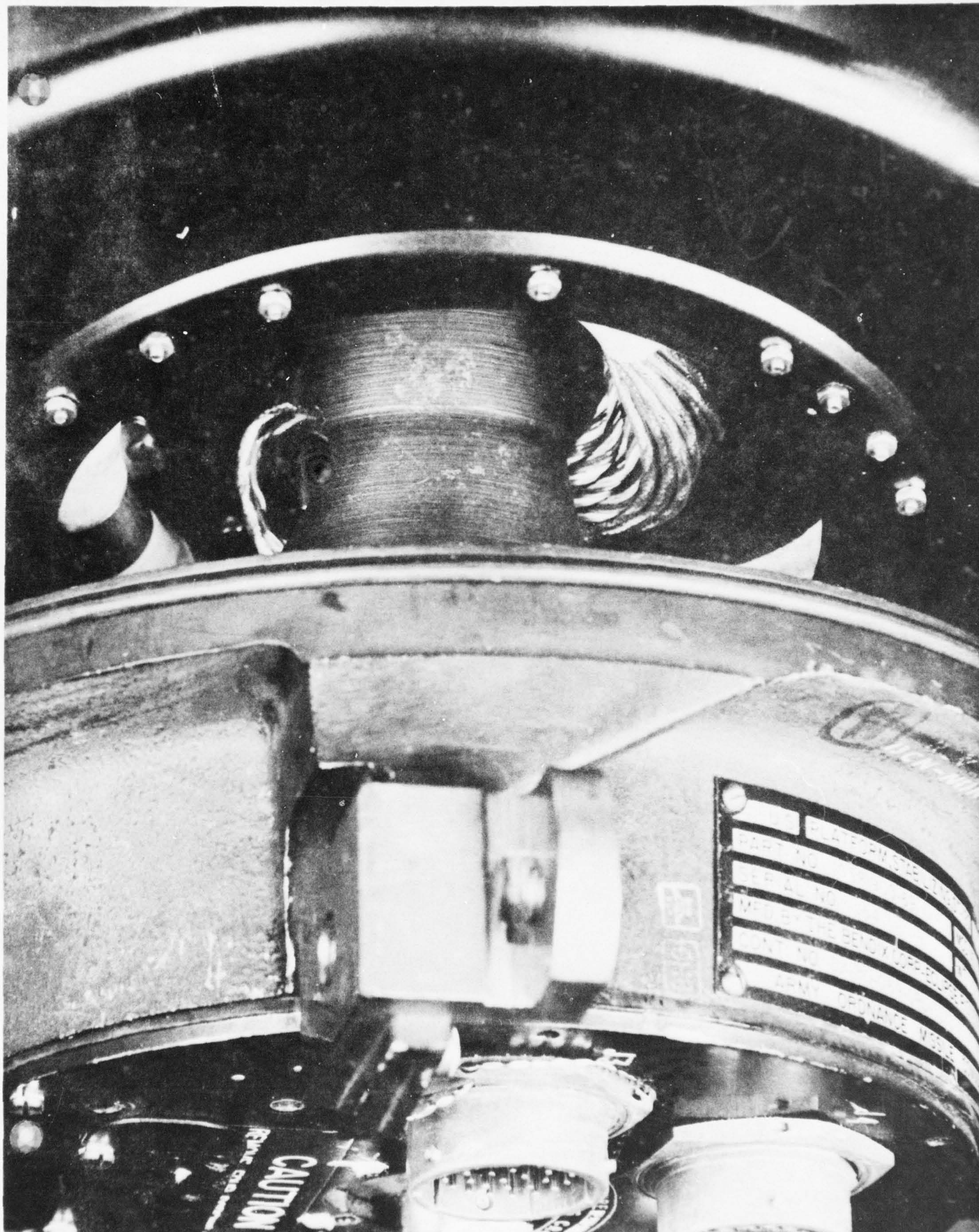
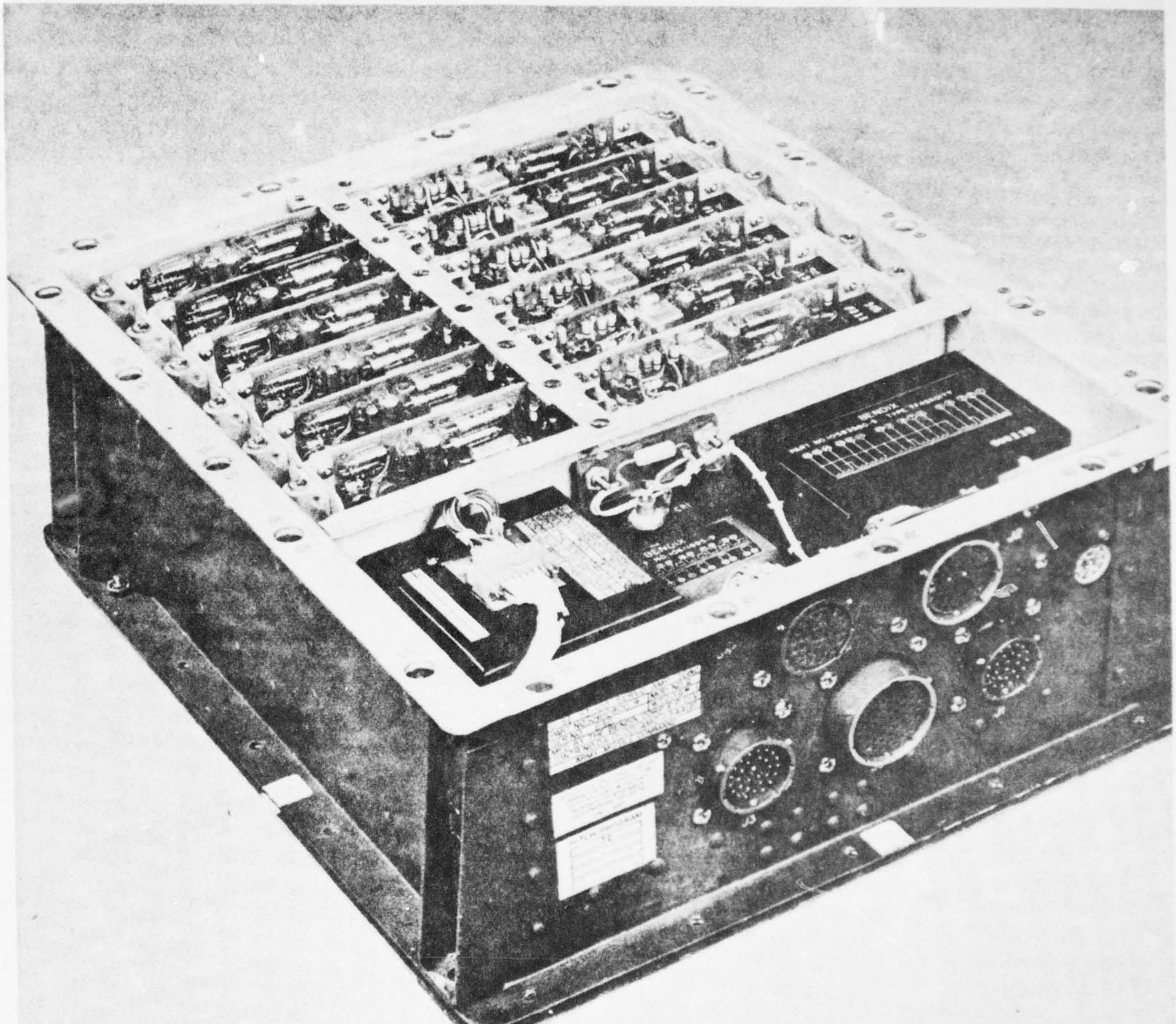


FIGURE 13



ST-120 PERSHING SERVO BOX

FIGURE 14

All amplifier cards, relay control assembly, and transformer power assemblies were removed and each subsystem was tested against original manufacturing procedures. Further disassembly of selected cards was conducted where all resistors, capacitors, diodes, transistors, and pots were removed without damaging the components. All of these components were then inspected for cracked cases, dielectric leakage on capacitors, and nicked leads. The components were then tested for meeting their electrical parameters, as specified in the original incoming inspection at time of fabrication.

Tantalum capacitors with marginal performance were X-rayed, and then dissected. The electro plated copper was examined to locate the weakness in the dielectric. Semiconductors with reduced performance were also X-rayed. A seal leak test was performed and then the units were dissected. Internal visual inspection covered contamination and workmanship.

The sealed relays were removed from their cards and examined on an individual basis. A seal leak test was performed along with a complete electrical test. Selected relays were then dissected to evaluate their internal condition. The internal inspection covered spring tension, contact adjustment, contact condition, surface contamination, discoloration, and insulation condition around the coil.

Some very interesting results were obtained from this investigation. The significant results were:

LEAP sample hardware showing effects of age/usage:

1. Cracked components on Hysol Ruggedized electronic cards as shown in Figure 15.

2. Cracked solder connections on electronic cards with Bifurcated terminal configuration.

3. Minor evidence of handling/service damage.

4. Transistors showed no evidence of internal physical or electrical deterioration.

5. Cover gasket material degradation.

6. Capacitor metallic flaking as shown in Figure 16.

LEAP sample hardware showing effects of environmental exposure:

1. Wire cable tubing insulation discolored.

2. No serious evidence of foreign or self-generated contamination.

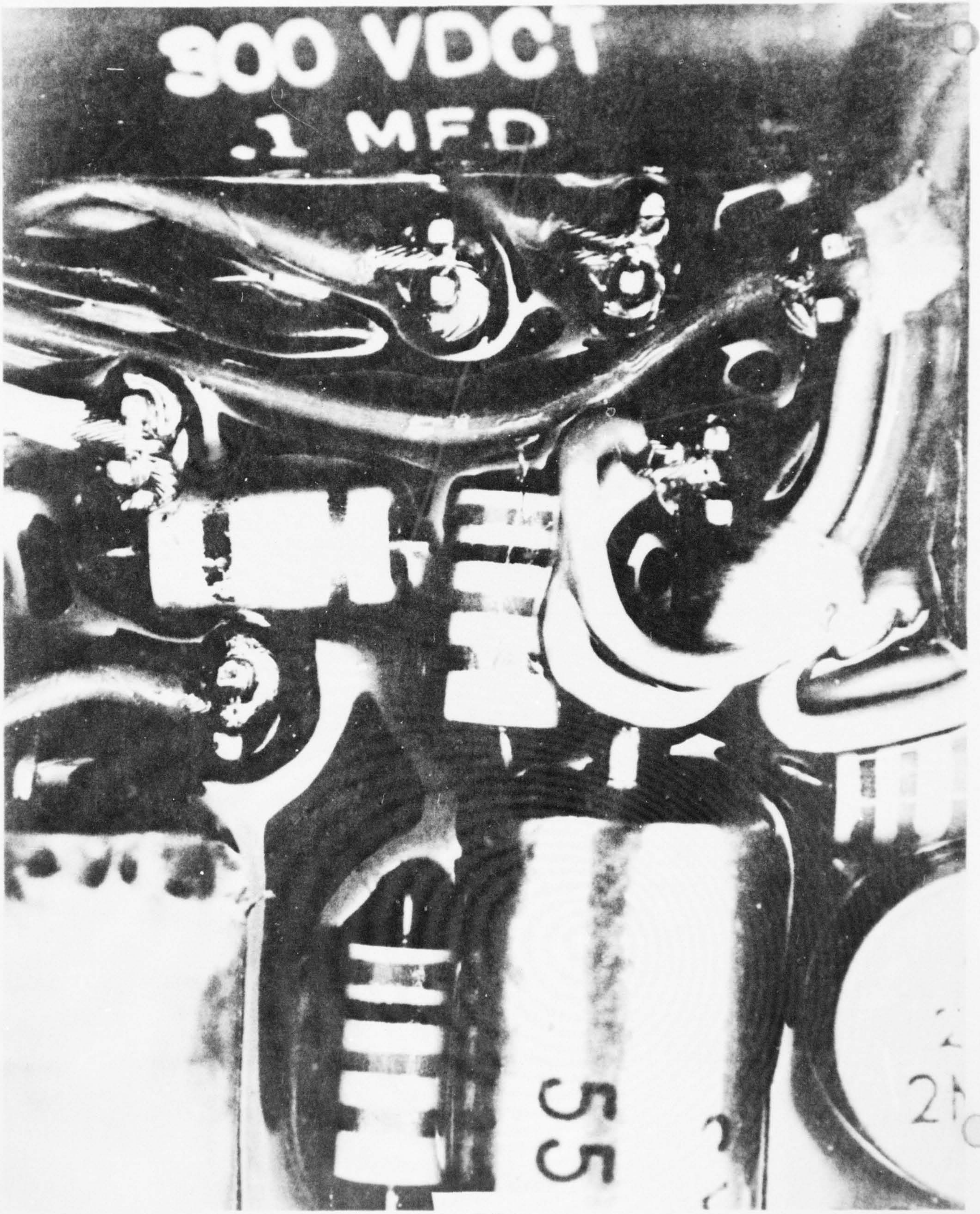


FIGURE 15

FIGURE 16

Some corrosion on the AN connector pins, see Figure 17, was caused by the silver plating migrating through the porous gold plate finish and eventually combining with gaseous sulfur in the atmosphere to generate silver sulfide. Also, the silver in contact with an insulating surface, in a humid environment and with an applied electrical potential, will move ionically from its initial location and redeposit in another location.

Servo Amplifier results:

From the analysis it was determined that the life of the servo amplifier could be extended through the 1980 time frame with minor remanufacturing of specific items. A correlation was found to exist between the number of failures and the operating time. This is graphically shown in Figure 18. The failures were mostly of a minor nature, consisting of gain changes. It was determined that the mechanical assemblies such as the amplifier case, transformer assembly, and relay assembly along with the wiring harness needed only a close visual inspection. During the Phase III remanufacture, it was determined that six (6) diodes should be replaced with a newer type and the diode body should be placed in PVC sleeving. The sleeving was determined as necessary to stop the cracking of resistors and diodes. The unequal temperature expansion between the Hysol ruggedizing and the component body caused the high stresses resulting in cracked components and the cracked solder connections of the Bifurcated terminals. Utilizing a less rigid ruggedizing material solved both problems.

CONCLUSIONS

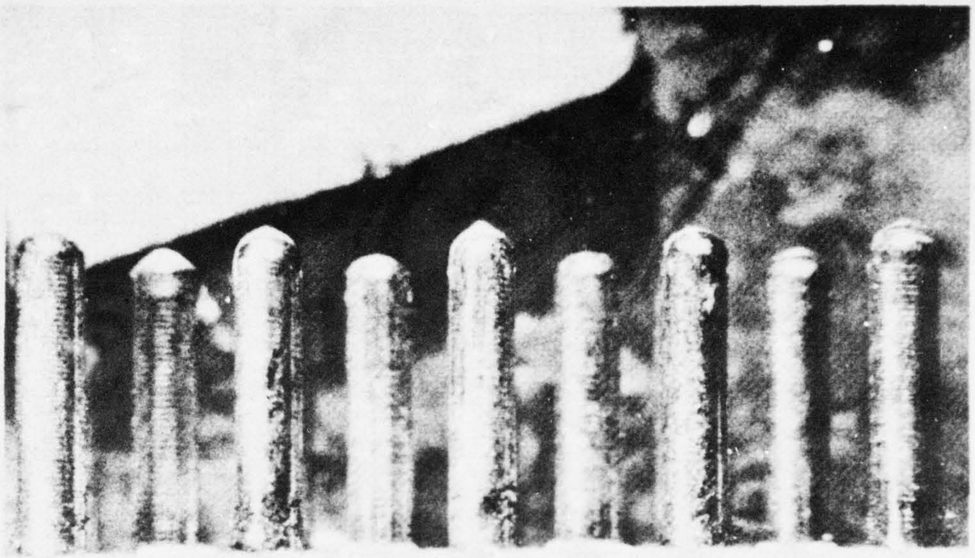
The results of the assessment program provided specific inputs for the Phase III remanufacture of the ST-120 stockpile. Accurate prediction of replacement component quantities, anticipated problems that would be encountered, and precise cost determination were only a few of the many conclusions obtained from the assessment program. Specific design changes and their functional significance were:

1. The rubber jacked aging rollers were changed to all metal design to eliminate fraying causing potential operational failures in the caging mechanism.

2. Microswitches used in the platform caging were redesigned by the vendor to eliminate internal debris. This debris caused high contact resistance resulting in faulty operation and/or defective readout.

3. The protective finish of black oxide and silicon grease coating was replaced by electroless nickel plating to eliminate corrosion (rust) on platform gimbals and main shaft. The rust was free to migrate to, and effect functional operation of, open gearing and bearings.

4. Gyro and accelerometer flex lead material was changed from 85% silver, 15% copper alloy to "BJ" gold, (11.99% gold ≠ 100 PPM beryllium) to eliminate



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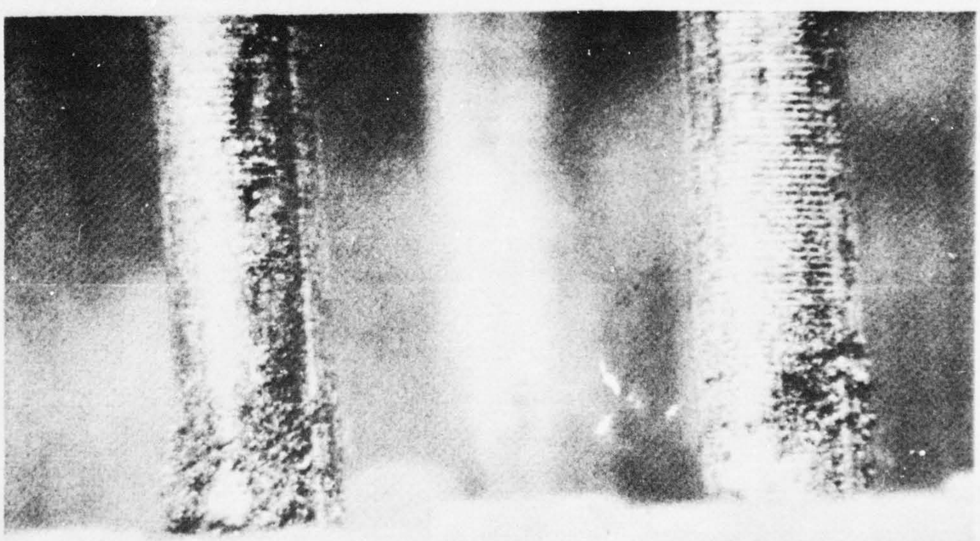

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FIGURE 17

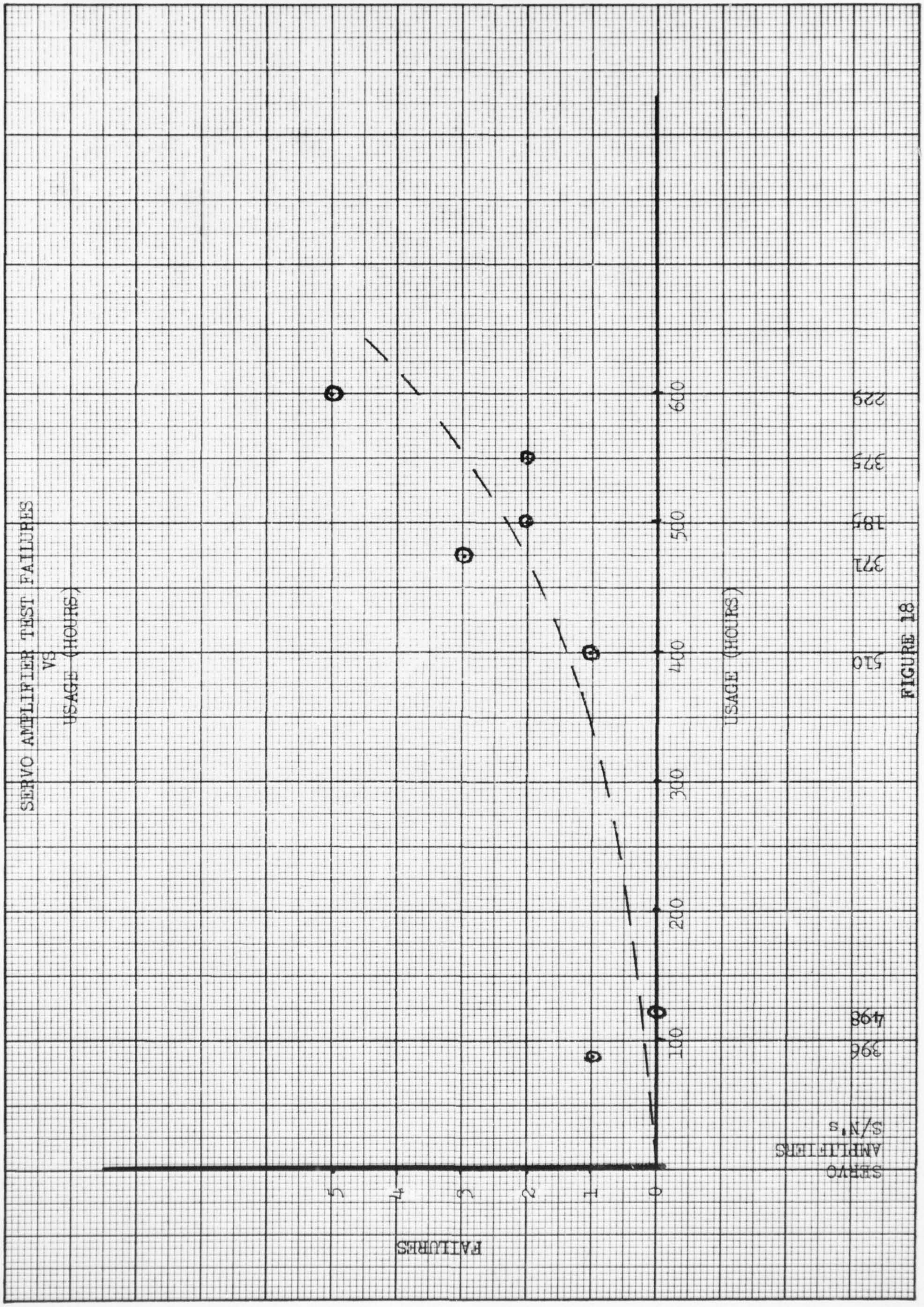
SERVO AMPLIFIER TEST FAILURES
VS
USAGE (HOURS)
FAILURES
0
1
2
3
4
5
USAGE (HOURS)
100
200
300
400
500
600
SERVO
AMPLIFIERS
S/N's
396
498
510
371
185
375
229

FIGURE 18

corrosion problems revealed during LEAP. Corrosion of silver-copper flex leads was due to reaction of the sulfur in the atmosphere and silver forming silver-sulfide in a form of whisker growth. In addition, the formation of copper oxide increased the resistance of the flex lead ribbon accelerating the sulfur/silver reaction. Contamination caused by migration of the loosely adhered particles could enter air bearing gaps resulting in gyro or accelerometer failure.

5. Miniature diodes (in hermetically sealed glass jacket) used on all servo amplifier cards and chassis terminal boards was changed to new configuration utilizing a new type diode covered with a protective plastic sleeve. The sleeve eliminated damage to the glass envelope caused by thermal stresses from the ruggedizing compound.

6. The type RC08 (MIL-R-11) sealed ceramic jacketed resistor was changed to a new resistor, type RCR05 (MIL-R-39008). The RC08 type resistor was replaced to eliminate damage to the ceramic jacket and failure of resistor element due to thermal stresses from the ruggedizing compound.

The Phase III remanufacture program was started in August 1972 and completed in March 1975. All ST-120 platforms in the PERSHING stockpile were cycled through the remanufacture process without jeopardizing the system's full strike capability. This highly successful remanufacture program was due to the accuracy and thoroughness of the analysis from the assessment phase.

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BRIEFING TITLE

AN IMPROVED TEST FOR MEASURING THE G-200 GYRO FLOTATION TEMPERATURE AND CENTER OF BUOYANCY

ANGELO TRUNCALE

In 1963 Mr Truncale joined a Systems Design Group at the MIT Instrumentation Laboratory or what is now the Charles Stark Draper Laboratory. He soon grew to be responsible for instrument test programs which verified analytical models and evaluated application concepts. These efforts were in support of various systems including SABRE and OAO.

In early 1974 he was given responsibility for the efforts of a group of engineers working with AGMC on the LN-12 Reliability and Maintainability Improvement Program, investigating ways of improving manufacturing and test techniques.

While he continues to support the AGMC program he is also involved in the definition and review of instrument test plans for the Air Force MPMS and MX programs as well as the Navy's Improved Accuracy Program (IAP). Finally, he is an Editor of CSDL's Technical Newsletter and works with the Laboratory's Education Department planning and coordinating technical classes and seminars. He holds a BS in Physics from Brooklyn Polytechnic Institute and prior to his joining the Draper Lab he was employed by the Sperry Gyroscope Company.

IMPROVING THE G-200 T_f AND C_b TESTS

by

Angelo Truncale

October 1975

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

ACKNOWLEDGMENT

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The author wishes to acknowledge the contributions of Bob Staats, Jim Heimrich, and Paul Billig of AGMC for their experienced insights, cooperation, and technical support. He also wishes to acknowledge the following at CSDL:

Bill Connolly for the investigation detailed in Section 3, and for designing the circuitry in the temperature-ramp generator.

Dick Hockney, for his electronic design assistance.

Dick Masters, for his analysis summarized in Appendix A.

Bill Murphy, for gathering the evaluation test data.

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

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SECTION 1

SUMMARY

As part of the Inertial Systems Logistics Improvement Study, CSDL reviewed the T_f and C_b tests performed on the G-200 gyro. The value of T_f, or flotation temperature, is normally extracted using the automatic-flotation-temperature test. This approach uses an internal indication of float*-to-case position to actively control the gyro temperature at the flotation point. However, because of acceptable build variations, the errors in the value of T_f extracted can be as large as 3°F. An alternative approach to this test was developed in which a temperature-ramp generator smoothly ramps the gyro temperature while the float-to-case position indication is recorded directly on the test station's recorder. This approach was shown to be accurate, and repeatable to 0.2°F. The use of the temperature-ramp generator was extended to include the C_b or center-of-buoyancy test. Traditionally, this test is performed by torque variations, and extracting a value in °/h/°F. By extracting the value of C_b from a continuation of the T_f test, the combined test time is reduced, while improved accuracies are achieved.

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* "Float" or Inner Gimbal—the wheel-supporting torque-summing member.

After confirming the applicability of the temperature-ramp generator, a set of hardware, which could be used in the production test area at AGMC, was developed. This included portable temperature-ramp generator circuits, and an interface box at each station. The interface box included the necessary switching circuits, signal-conditioning circuits, and as a special bonus, a wheel-power monitor to be used in support of other tests on the G-200. In all, the temperature-ramp generator and the interface box should significantly improve the capability of the G-200 test station.

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SECTION 2

INTRODUCTION

For some time, The Charles Stark Draper Laboratory h been involved in the Maintainability and Reliability Impro ment program at AGMC. A portion of this effort is directe at achieving cost-effective improvements in the testing of G-200 gyros. In this area the goals are:

(1) To review test techniques—investigating the validity of the tests and the accuracy or unce tainty of the results.

(2) To improve the inherent diagnostic capability the acceptance tests performed.

(3) To develop an optimum test sequence.

Towards these goals, several tasks are being addressed. I particular, the investigation of preferred gyro orientatio for drift and other tests provide the ability to separate error mechanisms in the results recorded. An active filte has been delivered and is being evaluated, which permits the separation of torque-signal anomalies from acceptable higher-frequency gyro noise. Tighter wheel-bearing specif cations[(2)] have been recommended which should significantl reduce the number of gyros requiring rebuild because of ba

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* Superscript numerals refer to similarly numbered referen in the List of References.

bearings. In the area of improved test accuracies, our energies have been directed towards the flotation-temperature-determination test (T_f) and the center-of-buoyancy test (C_b).[3] It is essential that the results from these tests be accurate, since the numbers gathered affect the weight-shave or balance-adjusting operation on the gyro. The weight-shave operation, in itself expensive, becomes all the more expensive if repeated weight-shaves/test cycle are required to converge on an acceptable final result.

The sections that follow describe these two tests (see Section 3), some of the mechanisms which cause errors in their results, and finally an alternate test approach developed at CSDL (see Section 4).

SECTION 3

DETAILS OF THE T_f AND C_b TESTS

The T_f and C_b tests are performed as separate tests in the acceptance-test sequence at AGMC. These two tests are described in Section 3.1 and 3.2.

3.1 The T_f Test

The T_f test is performed to determine the temperature at which the gyro float achieves neutral flotation. In the system, and during acceptance tests, the gyro is operated at T_f - 3°F. In the original definition of the T_f test, a conceptually valid approach was applied. This approach is to actively control the gyro temperature using an internal indication of float-to-case position. Once in a stable mode of operation, one has but to read the temperature at which the servo settles, and this temperature is T_f. Figure 3-1 shows the data recorded in a typical T_f test. These data show how, because of low float damping and long thermal time constants, the temperature oscillates about a settled point. In defining the T_f temperature point, the test operator extracts the average of this oscillation. Of itself, this approach is valid; however, as a result of taking a closer look at the float-to-case position-sensing mechanisms, it was found that errors as large as 3°F could be introduced.

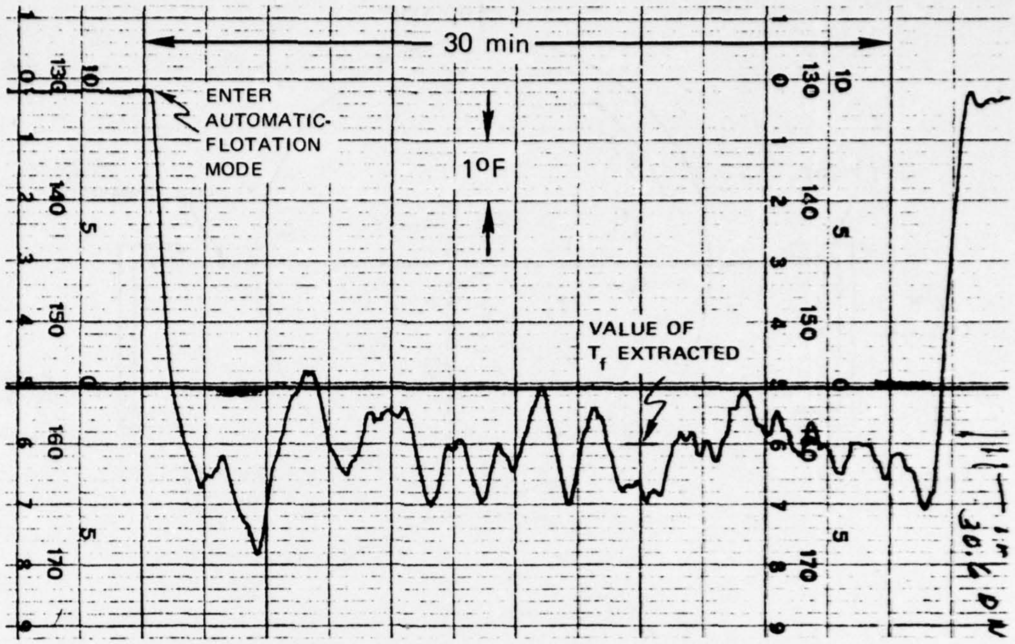

Figure 3-1. Typical trace of a T_f test performed in the automatic-flotation-test mode.

The transducer used to indicate float-to-case position is the Inner-Gimbal-Pickoff CenterTap (IGPOCT) voltage. It is important to form a good understanding of how the POCT and the gyro float behave at temperatures near the flotation temperature. Figure 3-2 is a schematic representation of three inner-gimbal (IG) float positions relative to the two IG pivots. The vertical free play (radial play) of the pivots is greatly exaggerated for clarity. The graduated scale in the center of the float is fixed to the case and represents the output of the IGPOCT relative to vertical-float position. Note that the mechanical center of float play between the pivots does not necessarily correspond to the electrical null of the POCT. The null position varies from unit to unit, dependent mostly on outer-gimbal pivot to jewel end play, and therefore is shown arbitrarily at two divisions above center.

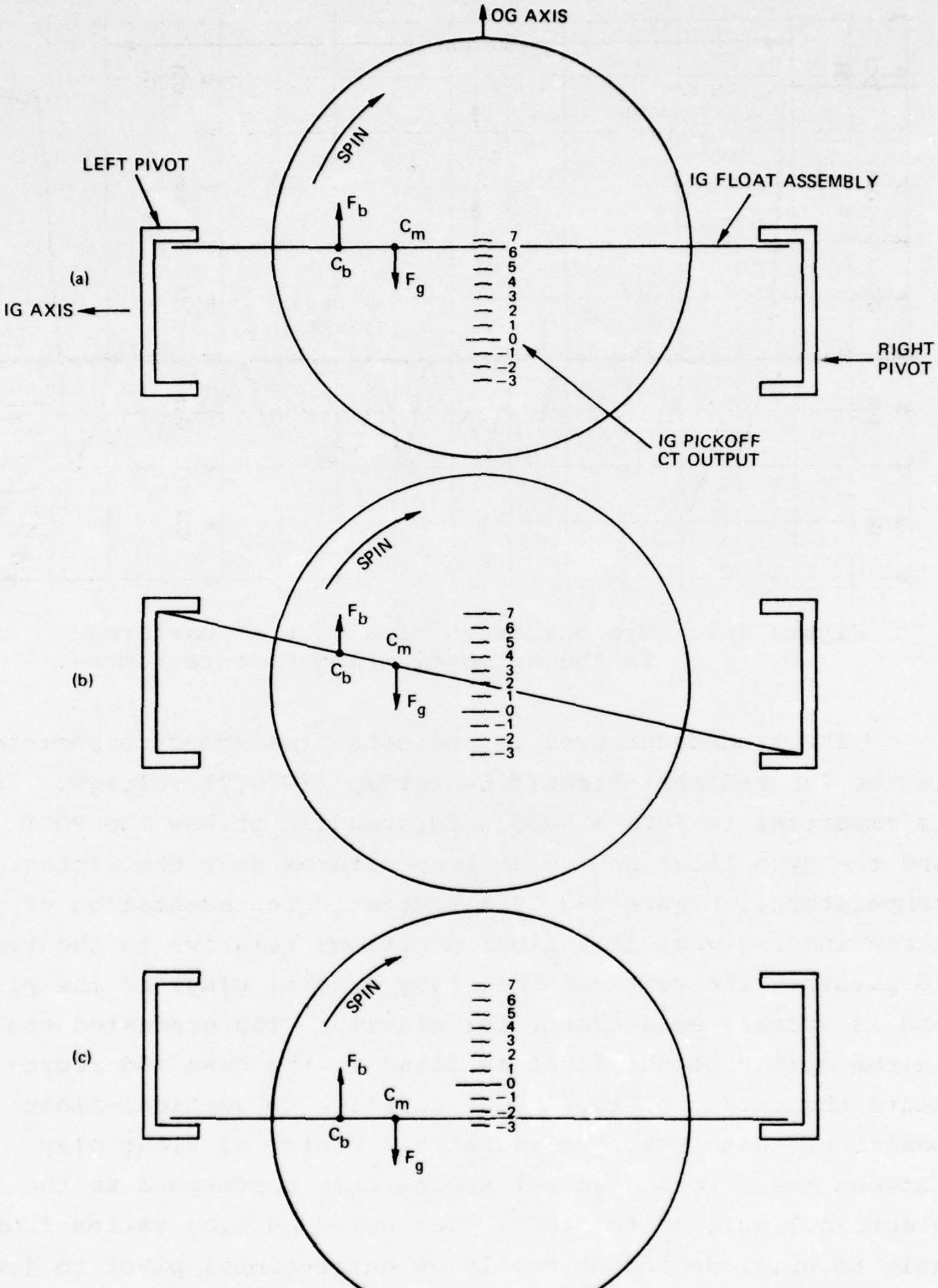

Figure 3-2. Inner-gimbal positions during an automatic-flotation-temperature test.

The center of buoyancy, C_b, and the center of mass, C_m, are also subject to some unit-to-unit variations and are similarly assigned arbitrary positions on the float as shown in Figure 3-2. At temperatures well below T_f, the float has positive buoyancy (see Figure 3-2(a)), and the forces acting on the float have a net upward resultant. As the temperature is increased, the buoyant force is reduced and the weight of the float begins to rotate towards the position shown in Figure 3-2(b). If we define this as temperature T_{ab}, we find that this may be equal to, or less than the flotation temperature. As the temperature is further increased, the float moves to the position shown in Figure 3-2(c). If we define this as temperature T_{bc}, this temperature will be equal to, or greater than T_f. Therefore, T_f is located somewhere between T_{ab} and T_{bc}.

Appendix A includes the necessary analysis which indicates that if the float is well balanced, then T_f lies halfway between T_{ab} and T_{bc}. A theoretical plot (based on the foregoing comments) of POCT output versus temperature is shown in Figure 3-3. Actual plots of POCT output versus temperature were recorded on several gyros as their temperature was slowly and uniformly increased. These plots, shown in Figure 3-4, indicate varying characteristics. Although the amount of time in which the float is in the position shown in Figure 3-2(b) varies, more significant is the spread in pickoff-centertap output-voltage levels, which can be seen in the various instruments. Between the instruments in Figure 3-4 for example, this spread is 8 millivolts. The question which becomes obvious in regard to the automatic-flotation-temperature test is: Over what section or sections of the curves of Figures 3-4(a), (b), and (c), does the float oscillate when in the automatic-flotation-test mode?

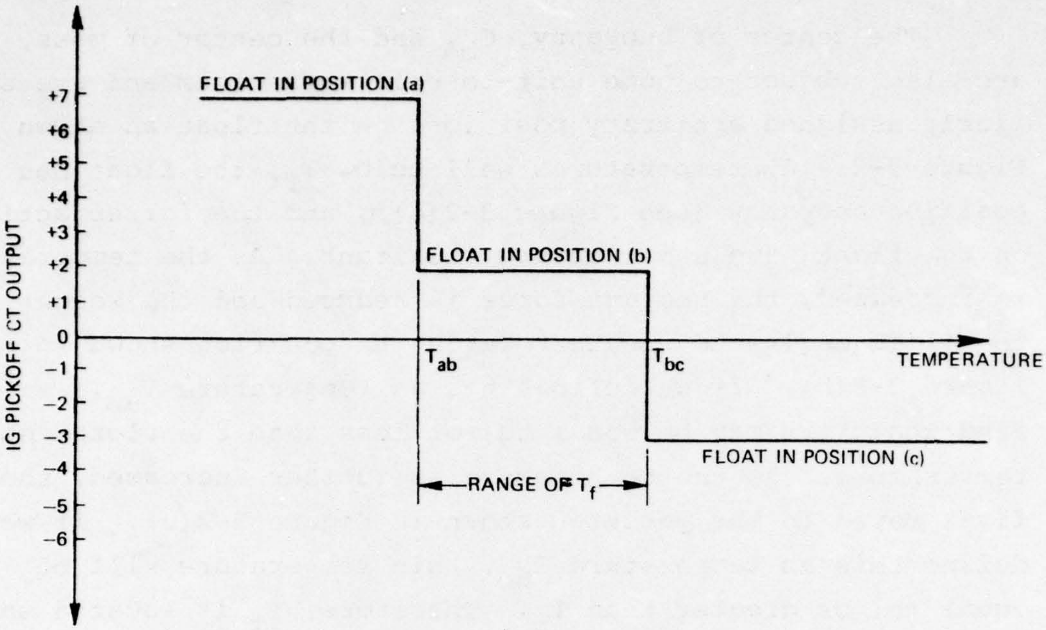

Figure 3-3. IGPOCT versus temperature (theoretical).

A block diagram of a theoretical representation of the major characteristics of the flotation loop is shown in Figure 3-5. Ideally, the loop is intended to keep the float oscillating about that position which results in zero pickoff-centertap voltage. However, because there are several external thermal inputs, the pickoff centerpoint has been offset in the standard test-station circuitry to produce enough error voltage to offset these errors. These errors are the sum total of steady-state thermal inputs and thermal sinks.

The theoretical curve which characterizes the steady-state open-loop pickoff to gyro-temperature transfer is shown in Figure 3-6. This curve shows gyro temperature as a function of the input voltage to the temperature-control circuitry. The area in which the flotation loop will operate is determined by the intersection of this curve and the

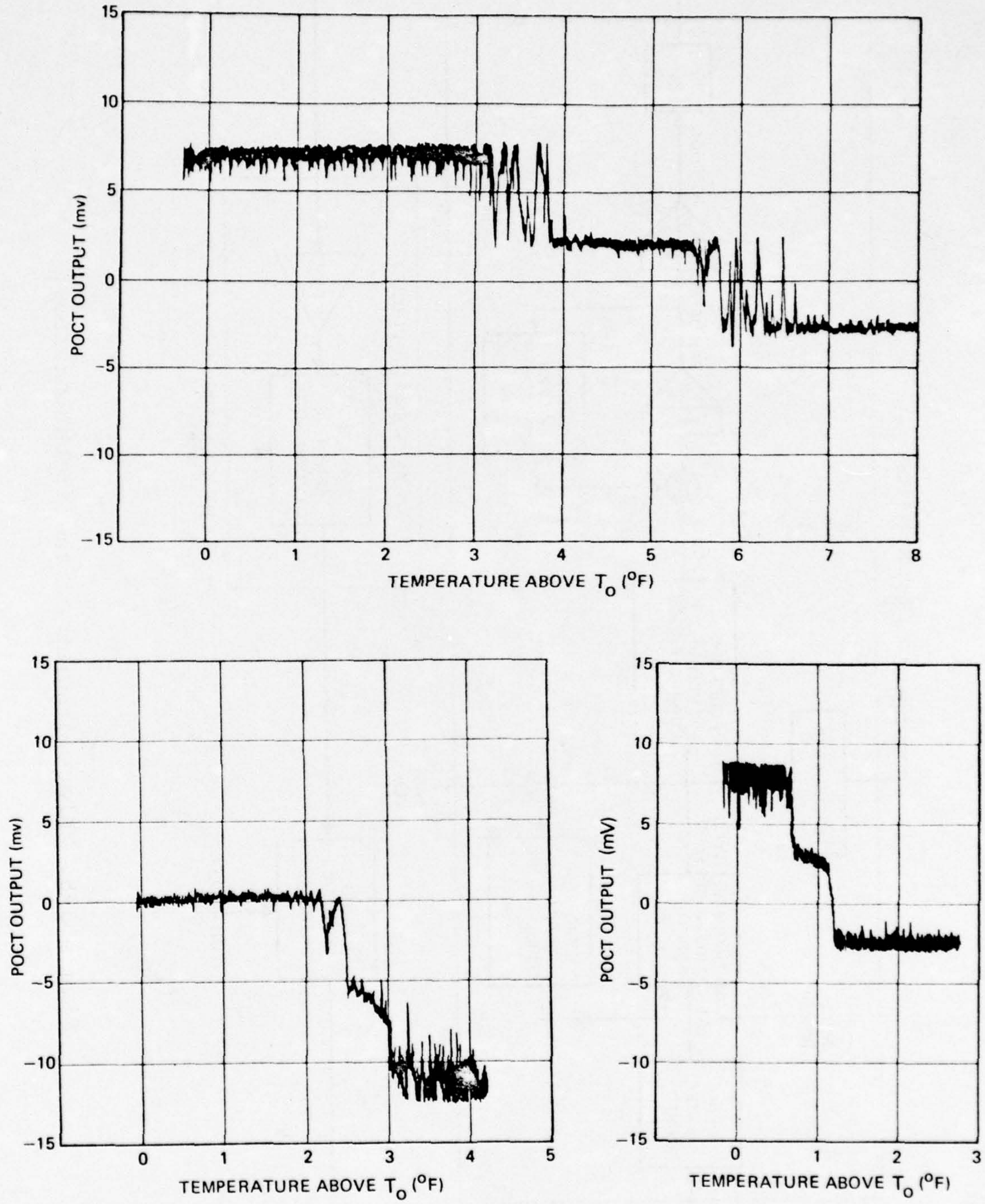

Figure 3-4. Actual plots of POCT versus temperature with increases in temperature.

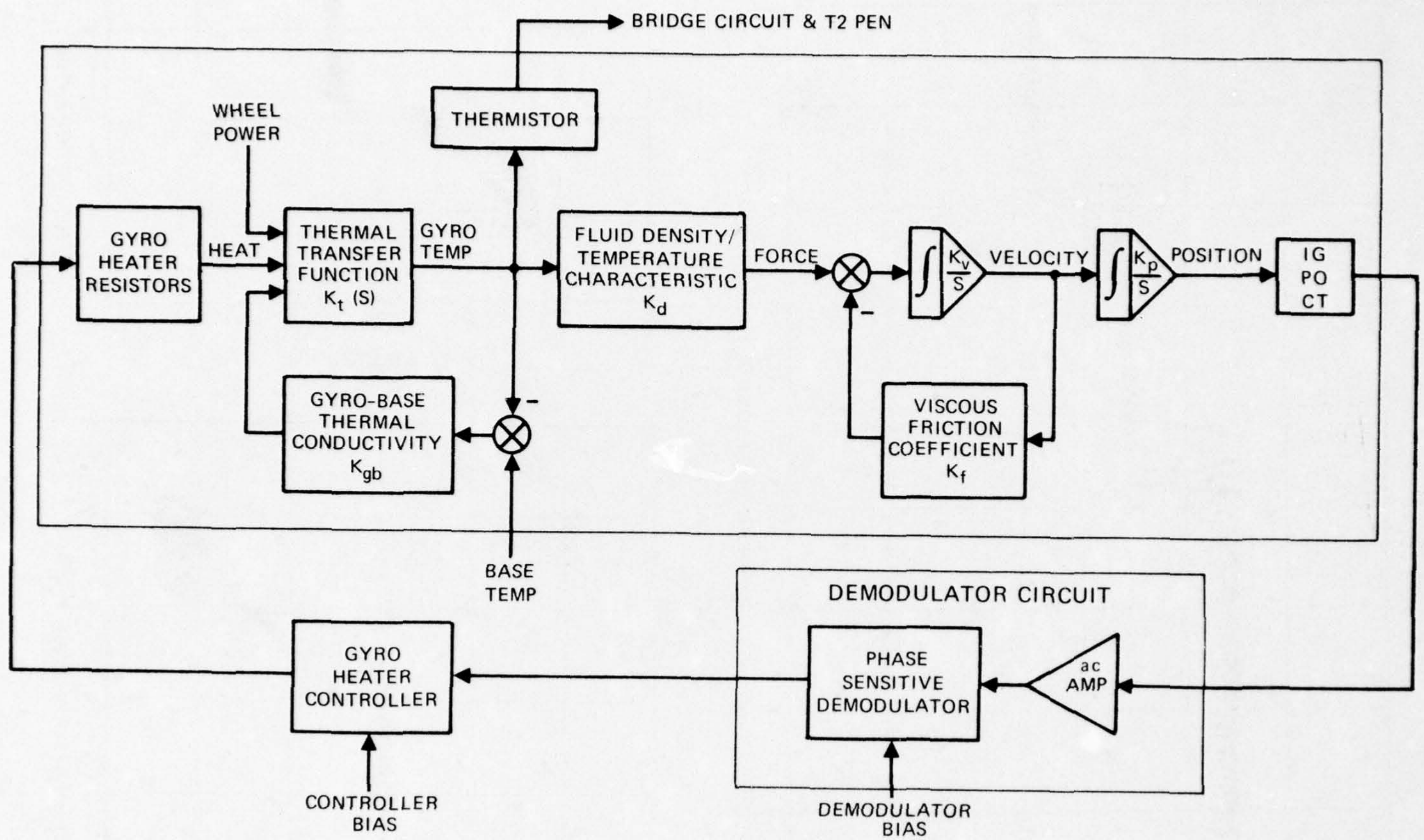

Figure 3-5. Block diagram of the flotation loop.

float-position curve, as shown in Figure 3-7. For each of the three gyros shown in Figure 3-4, this intersection in the measured flotation temperature occurred at or near temperature T_{bc}. In the course of normal testing, however, because both curves are variable functions of the gyro and the test station, and because the POCT is not normally recorded, it is not possible to tell from the flotation-test results themselves over which section of the float-position curve oscillations are occurring.

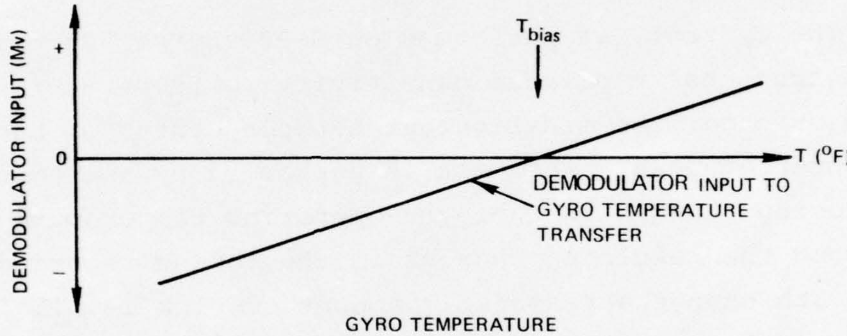

Figure 3-6. Demodulator input versus gyro-temperature open-loop transfer curve.

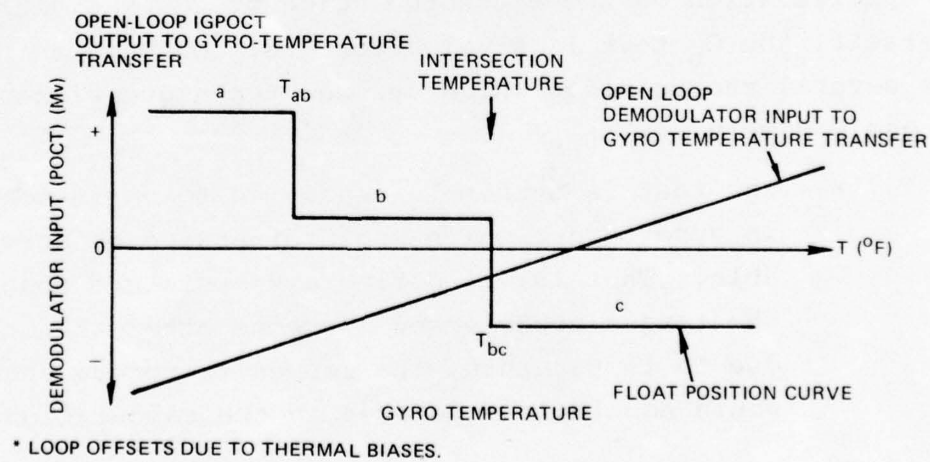

Figure 3-7. Float-position curve.

The variations in the float-position curve between gyros is a function of many variables. These variables include the vertical pivot-to-jewel end play, as well as the bias level at which the gyro torque-to-balance loop is operating. In tests conducted to investigate the latter, a sensitivity of 0.4°F per millivolt was determined. This is particularly significant in that one of the procedures for forcing the temperature loop to oscillate is to adjust the servo-loop bias.

3.2 The C_b Test

The C_b test, as performed on G-200 gyros, determines the instruments' unbalance sensitivity to temperature (°/h/°F) or, in essence, the misalignment between center of buoyancy and center of mass. The test is performed by incremently introducing changes in the gyro-operating temperature and observing the resulting changes in the torque recorded. After each change a reasonable amount of time is allotted for the instrument to settle thermally. A typical trace gathered during one of these tests is shown in Figure 3-8. Extremely accurate results are required from this test, since the specification on the extracted value of C_b is 0.01°F/h/°F. Of itself, the C_b test is straightforward; however, there were several shortcomings which our new technique wishes to address. Namely,

(1) The test is extremely sensitive to variations in gyro torque which would otherwise be acceptable. That is, if during a temperature change the torque experienced a change other than that due to temperature, the composite torque changes would nonetheless be used in the calculation of

the value of C_b. These torque changes are relatively common, since the temperature change is a step-change, and therefore introduces sizeable transients into the gyro-torque signal.

(2) The C_b test is time consuming because five gyro-temperature changes require 10 minutes to settle followed by a 15-minute torque recording at each new setting.

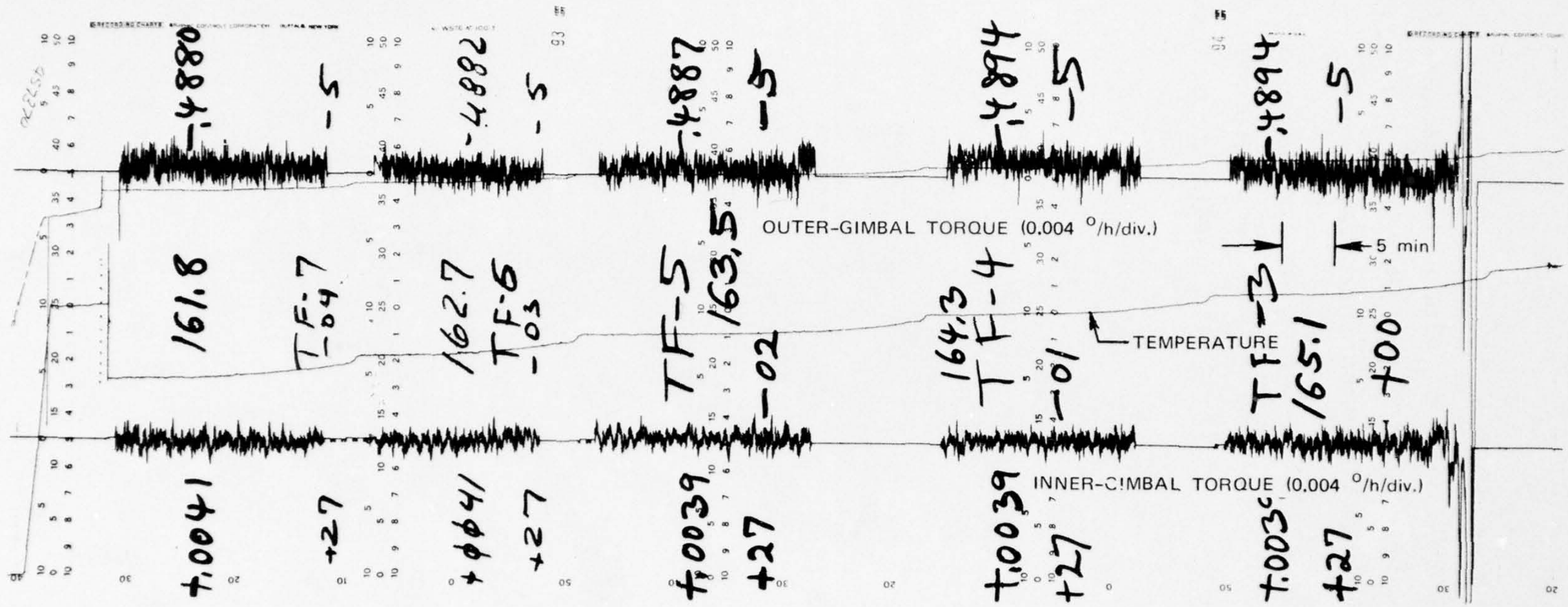

Figure 3-8. A typical C_b recorder trace.

SECTION 4

AN ALTERNATE APPROACH USING THE TEMPERATURE-RAMP GENERATOR

An alternate approach to the T_f and C_b tests was suggested during the investigation into the T_f tests. At that time, a temperature ramp was used in the characterization of the float-position signal. The float-position signal itself gave a good indication of when the instrument went through flotation, as the temperature ramp provided a smooth transition through the range of interest. The temperature ramp became the basis for the alternate approach. This approach would be relatively independent of variations in the pickoff-centertap zero-point location and the other subtleties which were deteriorating the quality of the standard T_f automatic-temperature test. In addition, because the C_b test also required variations in temperature, perhaps the same temperature ramp might also be used in a modified C_b test.

A temperature-ramp generator was designed and constructed. The prototype design shown in Figure 4-1 was devised to gather the necessary engineering evaluation data. It has the ability to ramp the gyro temperature between two selectable temperatures at rates from 0.1° to 0.8°F per minute. It introduces a ramping voltage signal into the temperature-control circuit at a second-stage amplifier so that the temperature-bridge error signal can still be monitored unaltered. That is, so that the temperature monitored on the recorder is still an indication of the instrument temperature.

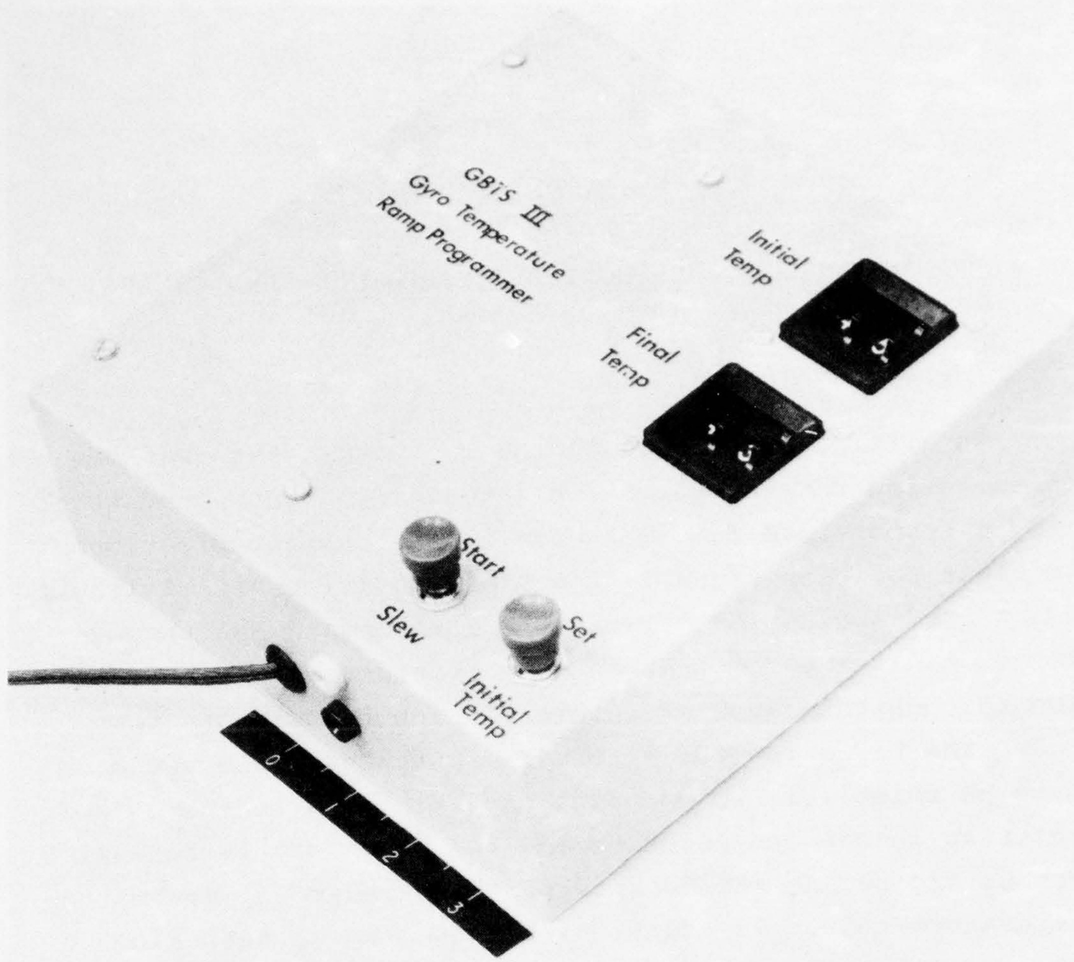

Figure 4-1. The temperature-ramp generator.

The questions addressed in engineering evaluation tests at CSDL were: First, whether the data gathered was valid, and second, at what speed should the temperature be ramped to permit the gyro to follow the temperature change without any significant lag. For the T_f test, data were gathered monitoring the pickoff-centertap signal as the temperature was ramped first from low to high and later from high to low. By comparing the behavior of the POCT during these

tests, it was possible to determine at what rate the gyro temperature could be ramped without exhibiting any significant hysteresis, or lag. Table 4-1 summarizes the spreads in T_f extracted at various rates as the gyro was ramped in these two directions. It was found that the 0.1°F/min. ramp was more than adequate in assuring that the pickoff-centertap signal was indeed reflecting the temperature recorded. The repeatability of the value of T_f extracted indicated uncertainties in the 0.1° to 0.2°F region. A typical trace of the T_f test performed with the temperature-ramp generator is shown in Figure 4-2.

Table 4-1. Flotation temperature differences observed at different ramp rates.

Ramp Rate (°F/min.)	ΔT_f* (°F)
0.1	<0.2
0.2	0.5
0.4	1.2

* (T_f negative ramp - T_f positive ramp)

The C_b test, performed using the temperature-ramp generator, was investigated next. Typical results are shown in Figure 4-3. These results were gratifying, particularly when torque disturbances were noted which could have otherwise corrupted the C_b value extracted in a test performed in the traditional way. The C_b test was performed on several gyros applying both the old and the new techniques. These results also compared favorably. With the engineering evaluation completed, the next task was to define a set of hardware which could be introduced into the acceptance-test station.

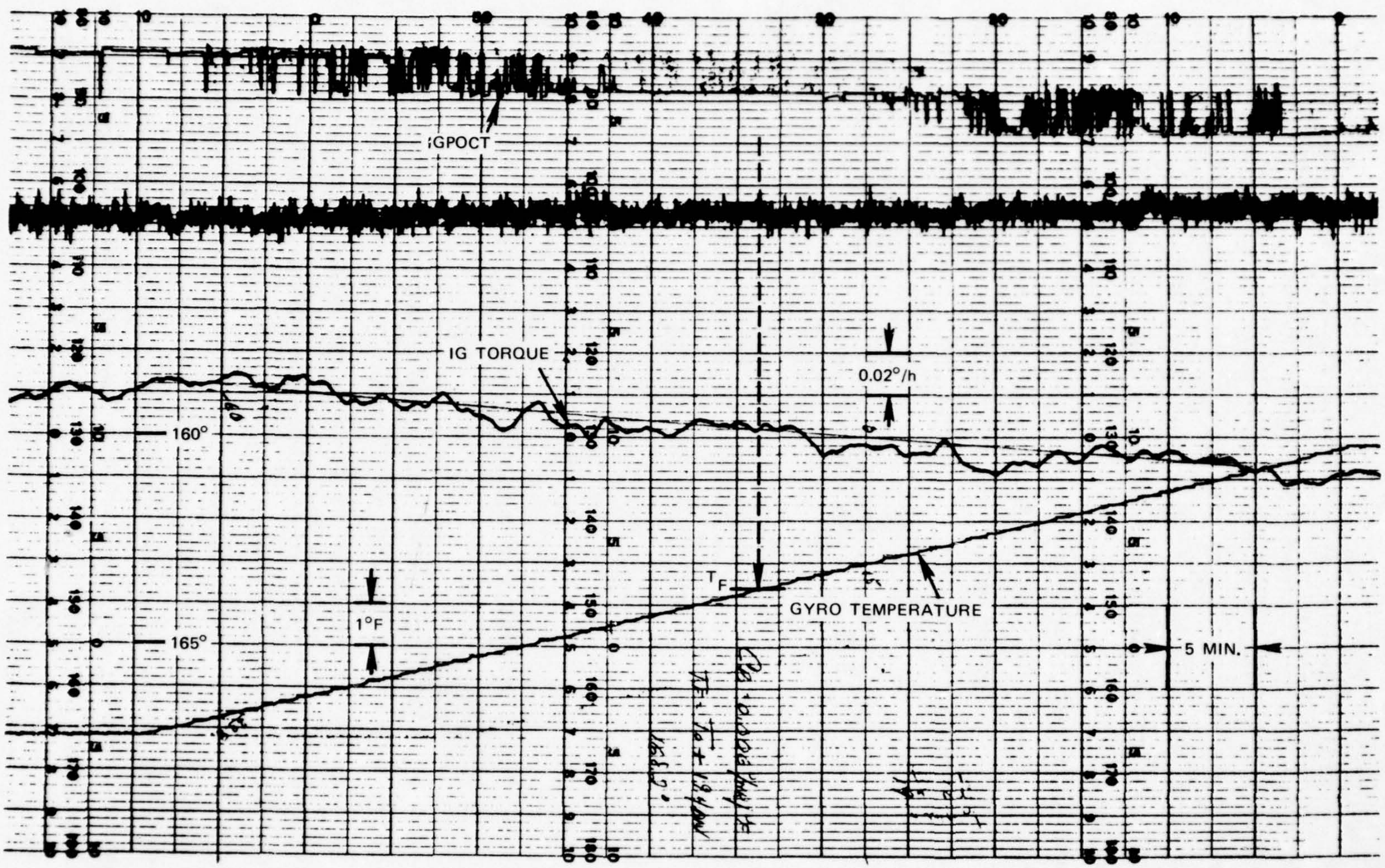

Figure 4-2. Typical trace of the T_f test performed using the temperature-ramp generator.

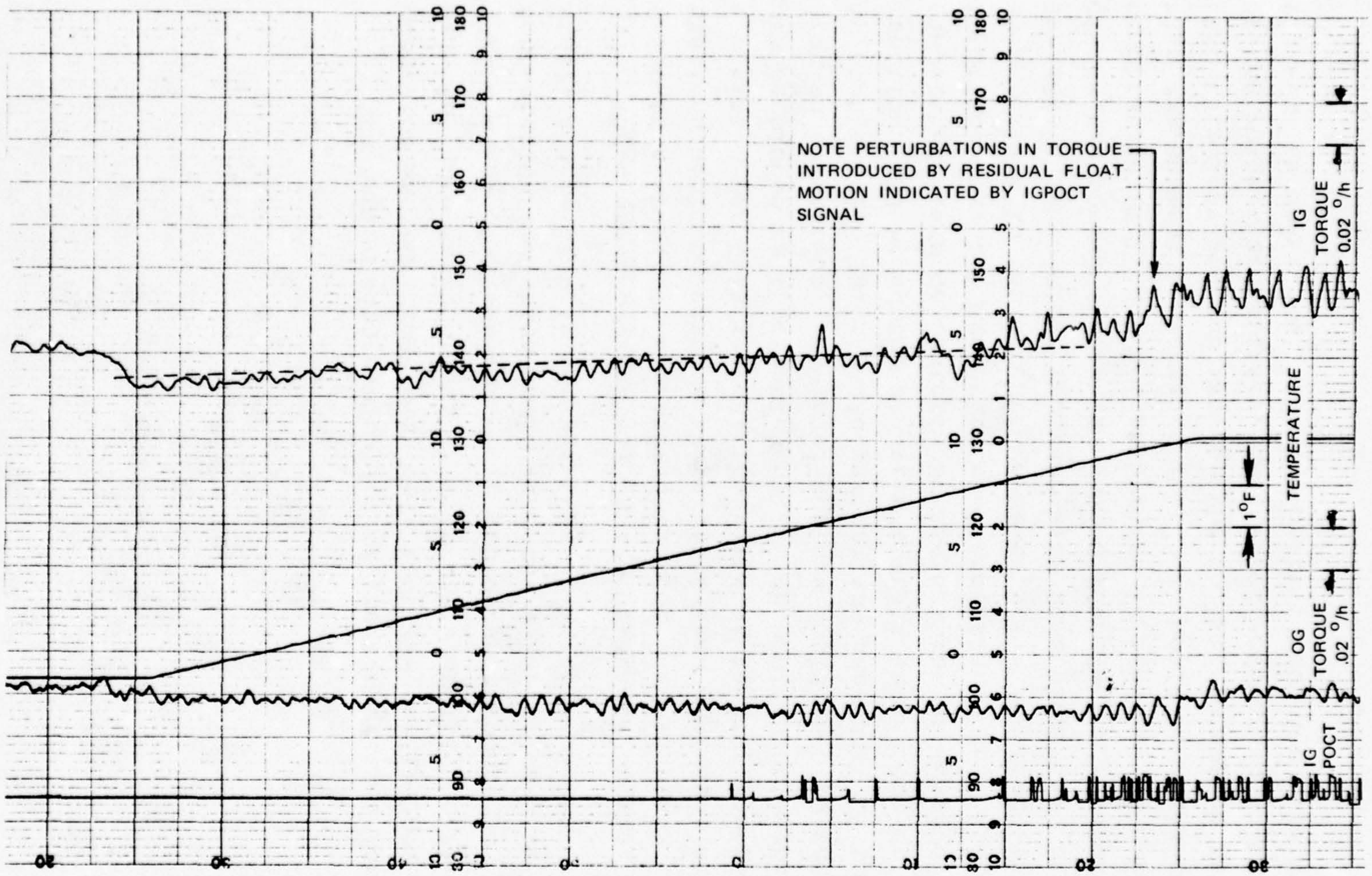

Figure 4-3. Typical trace of C_b test performed with the temperature-ramp generator.

SECTION 5

HARDWARE

The engineering evaluation of the temperature-ramp generator was performed with only temporary modifications to existing gyro test hardware. With its viability confirmed, hardware was now required which could be introduced on each test station and which would be both reliable, easy to install, and relatively inexpensive.

There are approximately 20 test stations in the AGMC G-200 test area. It was agreed that no more than six test stations would be using a temperature-ramp generator at any one time. For this reason, the temperature-ramp generator was developed as a portable unit which could be brought from station to station. An interface box would then be required at each station which would perform the necessary switching functions and bring the required signals in and out of the temperature-ramp generator. To appreciate the scope of this interface box, let us review the gyro-balance test station as it exists in the acceptance-test area. The test station includes a Servo-Riter recorder with four pens; one for each of the two torque traces (IG and OG), one which records gyro temperature (T_2), and a fourth which is time shared between base and ambient temperature (T_1). It would be necessary to take this last pen and provide the ability to switch in place of the temperature signals, the pickoff-centertap voltage signal. As configured, the Servo-Riter recorder also included

a temperature safety, which would shut the system down when the ambient temperature reached 10°F above operating. If the pen were to be used for a different function, this interlock would have to be mechanized within the interface box.

The pickoff-centertap signal, as recorded in the evaluation tests, was generated using a phase-sensitive voltmeter in the test station. In order to keep from continuously tying up this piece of equipment during the T_f and C_b tests, the interface box would also include a simple demod circuit. The circuits described, the temperature-interlock circuit, a demod circuit, and the necessary switching functions, were all packaged into a small box which fit neatly into the Servo-Riter recorder. This package is shown in Figure 5-1.

An improved diagnostic capability, as part of the normal acceptance test sequence, has been a goal of the CSDL effort at AGMC for some time. Since the interface box would have to be introduced on each test station, here was an opportunity to provide, with little additional cost, some additional hardware which would improve the diagnostic capability significantly. Since this was an engineering evaluation prototype version of a final interface box, we took the liberty of adding some circuitry which we felt to be valuable in the diagnostic area.

Pickoff-centertap signals recorded during bias-repeatability tests have been shown to be valuable in the diagnosing of pivot-to-jewel problems such as dirt and broken pivots. Because of this, the capability of recording either inner-gimbal POCT or outer-gimbal POCT on the Servo-Riter recorder was provided. Secondly, AGMC has, for some time, shown the value of correlating milliwattmeter traces to torque traces in the diagnosing of wheel-bearing problems.

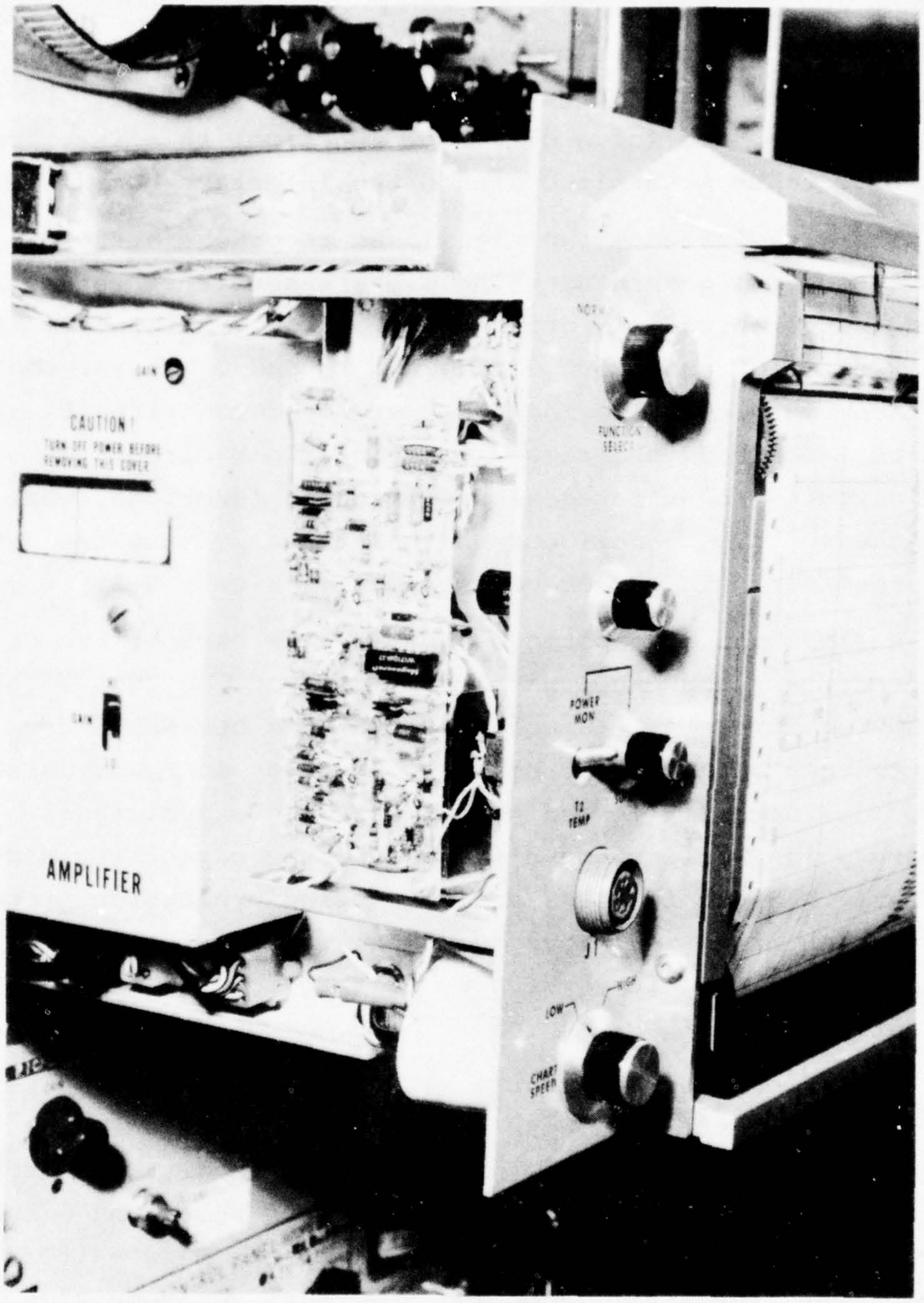

Figure 5-1. Test-interface box (cover off) installed in Servo-Riter recorder.

For the most part, this milliwattmeter trace need only be of a qualitative nature, indicating transients in power concurrent with transients in torque. The present approach used at AGMC is to have two commercial milliwattmeters in the test laboratory that can be rolled around to various test stations as required to provide the necessary diagnostic aid. While it would be worthwhile to introduce a milliwattmeter in each test station, the cost of commercially available units, with accuracies far beyond the needs, would be prohibitive. For this reason, a wheel-power monitor consisting of a simple $i \cos \theta$ demod was designed and also included in the interface-test box. The sensitivity and bandwidth of the wheel-power monitor, was matched to that of the milliwattmeter currently in use. Figure 5-2 shows a typical trace of the wheel-power monitor as compared to the milliwattmeter output.

While initially the interface box was required to simply interface the temperature-ramp generator to the gyro-balance test station, by including some relatively simple circuitry, its usefulness was expanded considerably. The cost of the entire modification, temperature-ramp generator, and interface box, comes to less than $1,000 per test station. This cost is relatively inexpensive when considered in the context of AGMC repair costs, where the typical recycle of a G-200 gyro can be expected to run in the $2,000 region. Obviously, by improving diagnostics and converging on a solution as quickly as possible, repair costs wasted on unnecessary repair cycles can be considerably reduced.

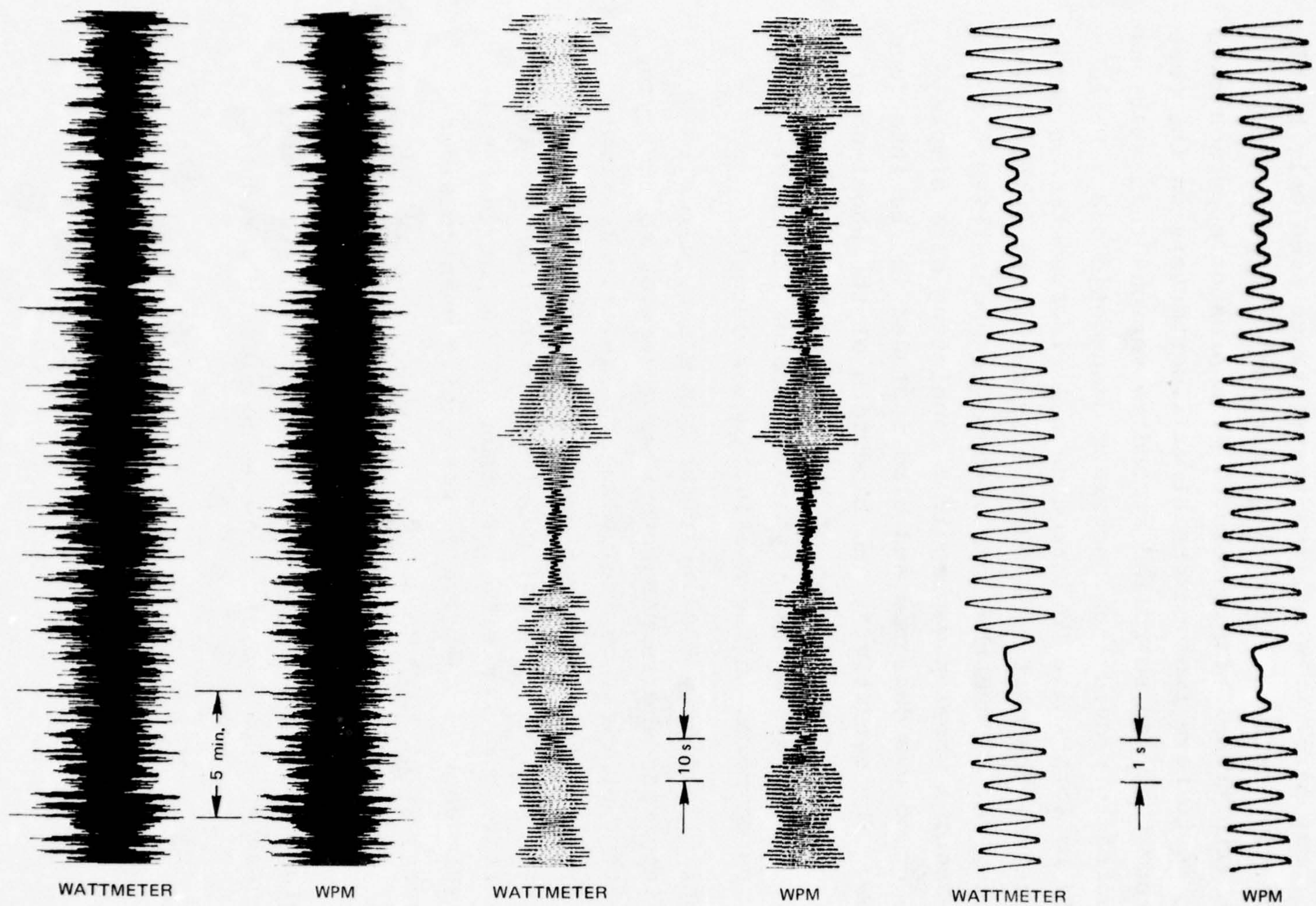

Figure 5-2. Comparison of traces using a commercial milliwattmeter and the wheel-power monitor.

APPENDIX A*

BALANCE AND FLOTATION ECCENTRICITY ERROR TORQUES

In Figure A-1, F_B is the flotation force,

$$F_B = V_F \rho_f$$

where

V_f = volume of the float

ρ_f = fluid density at average float temperature

$$\rho_f = \frac{1}{v_f} = \frac{1}{v_F(1 + \beta T)} = \frac{\rho_F}{1 + \beta T}$$

where

v_f = specific volume of the fluid

v_F = specific volume of fluid at flotation temperature

β = volumetric coefficient of fluid expansion $(\beta_{fluid} - \beta_{float})$

T = variation of fluid temperature from T_F

= $(T_x - T_F)$

ρ_F = fluid density at flotation temperature

---

* From CSDL internal memorandum from R. Masters to A Truncale, "Gyro Flotation Temperature Determination," 16 October 1974.

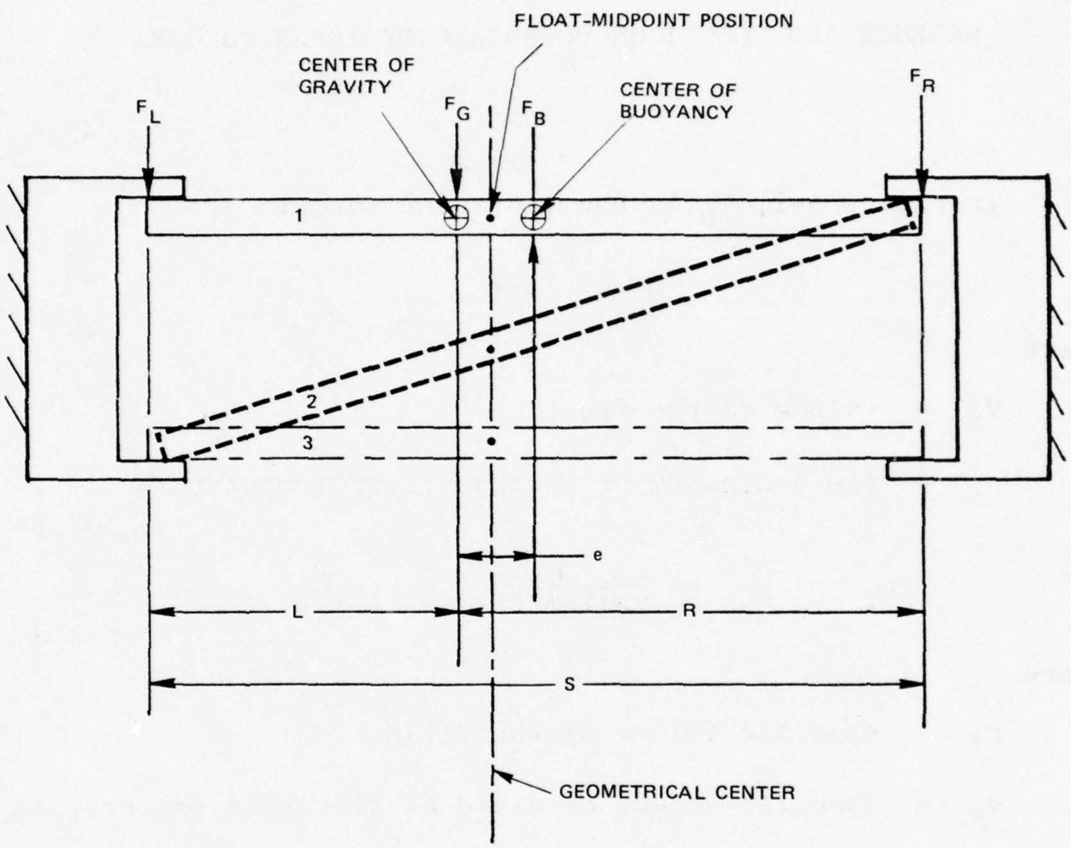

Figure A-1. Shaft flotation geometry.

Then,

$$F_B = \frac{V_F \rho_F}{1 + \beta T} = \frac{F_G}{1 + \beta T}$$

where

F_G = gravitational force on the float

Summing moments about F_R in Figure A-2,

$$\Sigma M_R = 0 = (R - e)F_B - RF_G - SF_L$$

T_1 is defined as where $F_L = 0$, and the left float end moves from the top to the bottom of the pivot restraint with increasing temperature.

Then,

$$(R - e)F_B = RF_G$$

$$F_B = \frac{RF_G}{(R - e)}$$

and

$$F_B = \frac{F_G}{(1 - \beta T)}$$

from above.

$$\frac{RF_G}{(R - e)} = \frac{F_G}{(1 - \beta T)}$$

$$(1 - \beta T) = \frac{(R - e)}{R}$$

$$T = \frac{\frac{(R - e)}{R} - 1}{\beta}$$

$$= \frac{(R - e) - R}{R\beta}$$

$$= \frac{-e}{R\beta}$$

Here,

$$T = T_1 - T_F$$

$$= \frac{-e}{R\beta}$$

or

$$T_F - T_1 = \frac{e}{R\beta}$$

Summing moments about F_L,

$$M_L = 0 = LF_G + SF_R - (L + e)F_B$$

T_2 is defined as where $F_R = 0$ and the right end moves from the top to the bottom of the pivot restraint with increasing temperature. Similarly it can be shown that

$$T_2 - T_F = \frac{e}{L\beta}$$

Then,

$$T_2 - T_F + T_F - T_1 = \frac{e}{L\beta} + \frac{e}{R\beta}$$

$$T_2 - T_1 = \frac{e(R + L)}{\beta RL}$$

and

$$e = \frac{\beta RL(T_2 - T_1)}{R + L}$$

If $R \simeq L$,

$$e \simeq \frac{\beta S^2(T_2 - T_1)}{4S}$$

$$= \frac{\beta S(T_2 - T_1)}{4}$$

Also,

$$\frac{(T_F - T_1)}{(T_2 - T_F) + (T_F - T_1)} = \frac{e/\beta R}{e/\beta L + e/\beta R}$$

$$\frac{T_F - T_1}{T_2 - T_1} = \frac{eL}{eR + eL}$$

$$= \frac{L}{R + L}$$

Thus, the location of T_f in the span from T_1 to T_2 depends on the dry balancing of the floated member, which information may be available through manufacturing specifications. If the float is well balanced, then T_F is in the center of $T_2 - T_1$.

LIST OF REFERENCES

1. Pettersen, R. J., and A. Truncale, Gyro Balance Test Station Torque Filtering, Charles Stark Draper Laboratory Report C-4205, October 1974.

2. Truncale, A., Reduced G-200 Repair Costs Through More Stringent Bearing Screening, Charles Stark Draper Laboratory Report C-4368, April 1975.

3. Connolly, W., A Review of the Automatic Flotation Test of the G-200 Gyro, Charles Stark Draper Laboratory Report C-4316, February 1975.

4. Charles Stark Draper Laboratory internal memorandum from R. Masters to A. Truncale, "Gyro Flotation Temperature Determination," 16 October 1974.

BRIEFING TITLE

GEANS TEST RESULTS DEMONSTRATE PERFORMANCE COMPATIBLE WITH INCREASED AIRCRAFT MISSION EFFECTIVENESS REQUIREMENTS

PAUL HALL

Mr Hall received a BS in Electrical Engineering from the University of Illinois in 1960 and has been associated with the development of inertial navigation systems for 15 years. His experience includes development of the Centaur Guidance System, the Dynasoar Navigation System, and the Inertial Navigation System for the YF-12, the Air Force MACH 3 Interceptor.

Mr Hall has been associated with ESG technology since 1965 and his significant contributions to the ESG technology development were officially recognized by the H. W. Sweat Engineer Scientist Award in 1966.

GIMBALED ELECTRICALLY SUSPENDED GYRO AIRCRAFT NAVIGATION SYSTEM

By

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INTRODUCTION

Precision Navigation is no longer a dream of the future. Current and projected military aircraft missions require precise (position, velocity, and attitude) reference for maximum effectiveness and utilization of associated sensors. GEANS (Gimbaled Electrically Suspended Gyro Aircraft Navigation System) laboratory and flight test results demonstrate accuracy compatible with those requirements. Flight tests have been conducted in F-4, C-141 and C-135 aircraft at CIGTF, Holloman AFB, as well as in P-3C, RC-135, 727 and U-2R aircraft under special applications. The significance of the flight tests is the demonstration of consistent "spec type" performance at 0.1 nm/hr position error and 2.0 ft/sec velocity error in various missions. The mission variations were:

- Long Term (10-14 hours)
- High rate maneuvers in the F-4
- Polar Navigation
- High Latitude Self Alignment
- Ground Alignment
- In-Air Start-up
- In-Air Alignment

The significance of the laboratory tests is the demonstration of similar performance in a laboratory and flight test environment, which is primarily due to the high quality inertial components.

This paper will present the previously classified results of the GEANS laboratory and flight tests and show the evolution of its maturity through a logical series of developmental and preproduction programs.

Operational advantages, maintenance features, typical applications and the use of computer simulations to predict system performance are also discussed. These aspects of the GEANS further demonstrate how this sytem can be used to advantage.

Schedule of ESG Airborne System Development

Use of ESG for airborne applications has been under Air Force development with sponsorship by AFAL since 1959. The first series of R&D contracts culminated in a prototype system that was laboratory tested at Honeywell prior to flight testing on a C-124 out of Wright-Patterson AFB from October 1966 to April 1967. This flight test was very successful and culminated in the GEANS development which occurred from June 1968 until April 1971.

The GEANS program produced three production prototype systems that were flight tested at CIGTF, Holloman AFB in 1971, 1972 and 1974. The aircraft used were F-4, C-141, and NC-135.

Following the GEANS flight tests was a program to redesign certain portions of the electronics to make them more producible without degrading reliability or performance. Two additional systems were built and all five systems were optimized in this manner. The resulting equipment was used on programs with P-3C, RC-135, U2R and 727 aircraft.

The SPN/GEANS Program (Standard Precision Navigator) was initiated in 1973 to further optimize the GEANS design for increased reliability, lower acquisition and maintenance costs and radiation hardening without affecting performance. Eight SPN/GEANS are being built by the Air Force for test and evaluation. The systems are production models. It is the goal of the SPN Program Office to make the system an Air Force inventoried system for applications needing a precision inertial navigator. The current Program Manager at AFAL is Mr. Ron Ringo who was responsible for initiating the SPN/GEANS program. The first system was shipped to CIGTF as scheduled on 15 October 1975.

Since the initial GEANS Contract, the Air Force and Honeywell have structured the development as a balanced design of reliability, maintainability, producibility and performance to provide low cost of ownership. To this date the program goals have been met in these areas and the forthcoming SPN flight test is the culmination of the development and test of the SPN/GEANS design.

ESG AIRBORNE SYSTEM

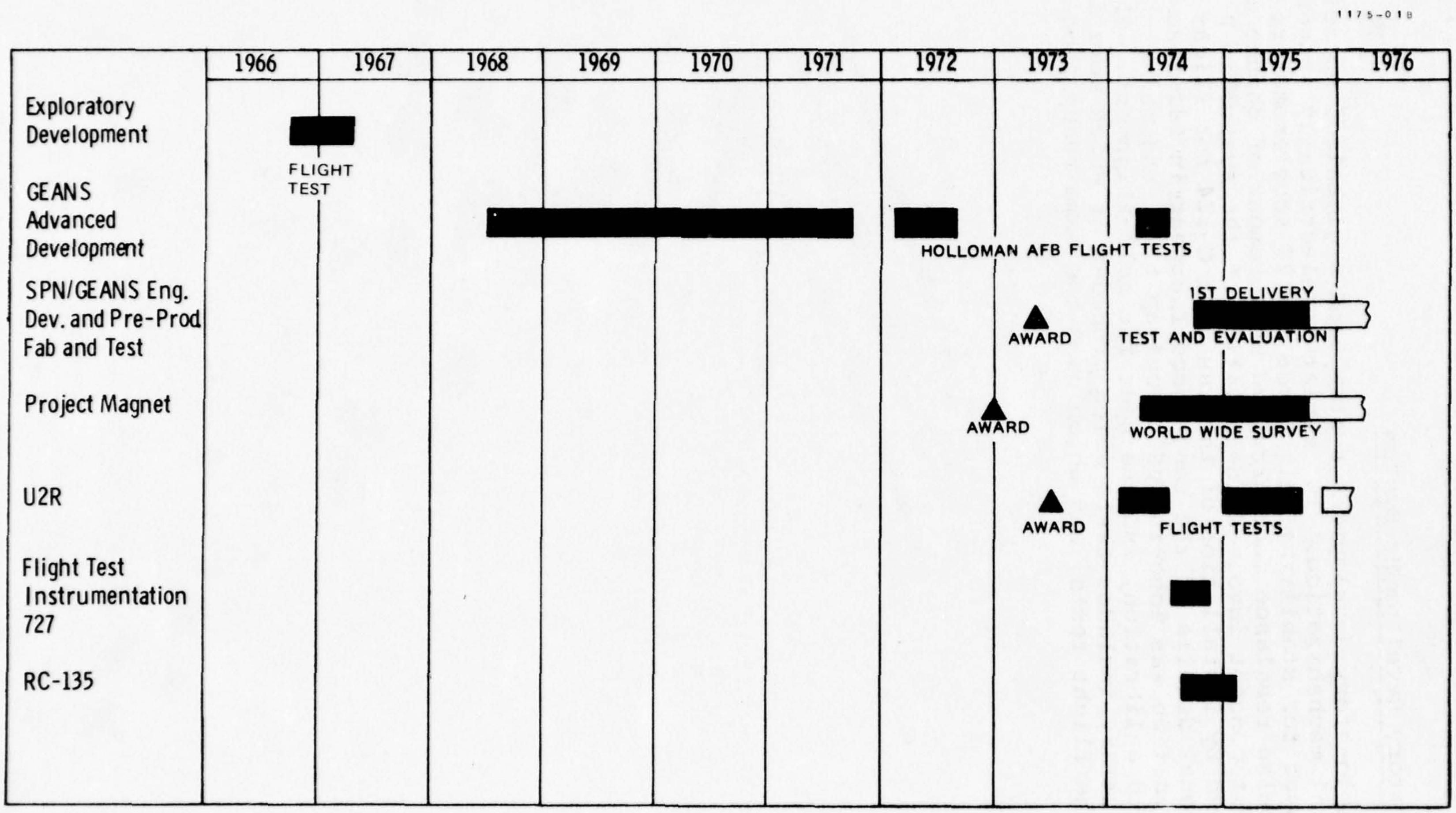


FIGURE 1

Exploratory Development System

The exploratory development system used a gimbaled, space stable pure inertial mechanization. Two miniature electrically suspended (MEGs) were used for stabilization. Three GG 177 accelerometers operating in a pulse rebalance mode provided measurement of change in velocity. The test concept involved installation of the system in a van, followed by installation of the van in a C-124 for flight test. Additional details of the test concept appear in Reference A. Typical reaction time was long including spinup time, thermal stabilization, and gyro calibration, and one hour for self-alignment. The laboratory test summary includes tests which preceded or which were interspersed with the flight tests, and which used the same runup procedures.

EXPLORATORY DEVELOPMENT SYSTEM

1175-03

COMPOSITE OF THIRTEEN LABORATORY TESTS
JUNE 1966 THROUGH MARCH 1967

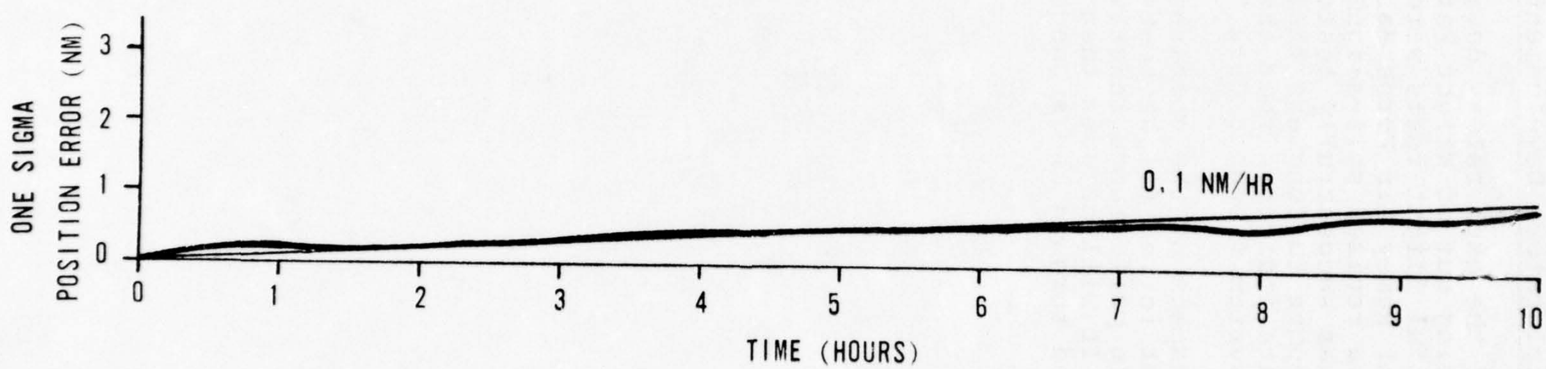


FIGURE 2

Flight Test Exploratory Development System

Flight test of the exploratory development system was performed in a C-124 operating out of Wright Patterson Air Force Base, Ohio. Twelve successful flight tests were obtained, including a low latitude exercise out of Ramey Air Force Base (Puerto Rico). Late in the test program, a revised self-alignment routine, which required only ten minutes, was successfully tested. These test results were the basis for a report to Congress that "the preliminary analysis of the flight test data indicated that the ESG system accuracy exceeds that of any other system flown to date."

An important aspect of the combined laboratory and flight test results is that in the flight test environment the system experienced very comparable performance relative to the demonstrated laboratory performance. It will be seen that this highly desireable characteristic persisted through the subsequent developments.

EXPLORATORY DEVELOPMENT SYSTEM

1175-02

COMPOSITE OF TWELVE FLIGHT TESTS
OCTOBER 1966 - APRIL 1967

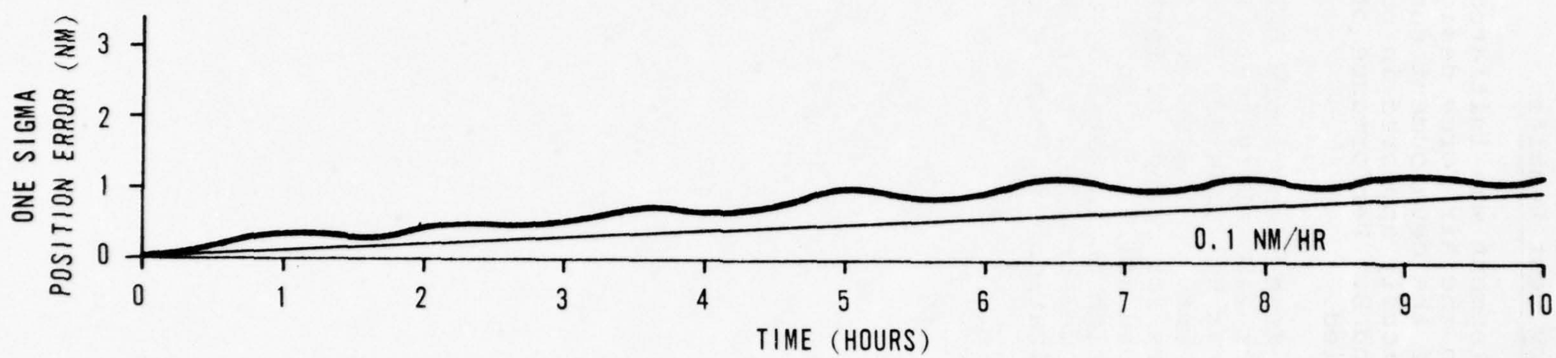


FIGURE 3

GEANS Laboratory Test Results

The GEANS development was initiated in 1968. The system was subsequently given the Air Force designation of AN/ASN-101. Detailed descriptions of the development concepts and of the resulting hardware have previously appeared in published literature; for example, References A and B. Performance of the system has only recently been declassified.

The summary of GEANS laboratory performance includes the results from twenty-four laboratory tests which were interspersed with flight testing at Holloman Air Force Base in 1972. Demonstrated reaction times were of the order of fifty-five minutes including fourteen minutes for runup and forty-one minutes for thermal stabilization and self-alignment. Note that the gyro calibration on each run, which characterized the earlier exploratory development tests has been deleted, and that the time required for runup and thermal stabilization has been reduced.

SUMMARY OF AN/ASN-101 (GEANS) HOLLOMAN LAB TESTS

1175-04

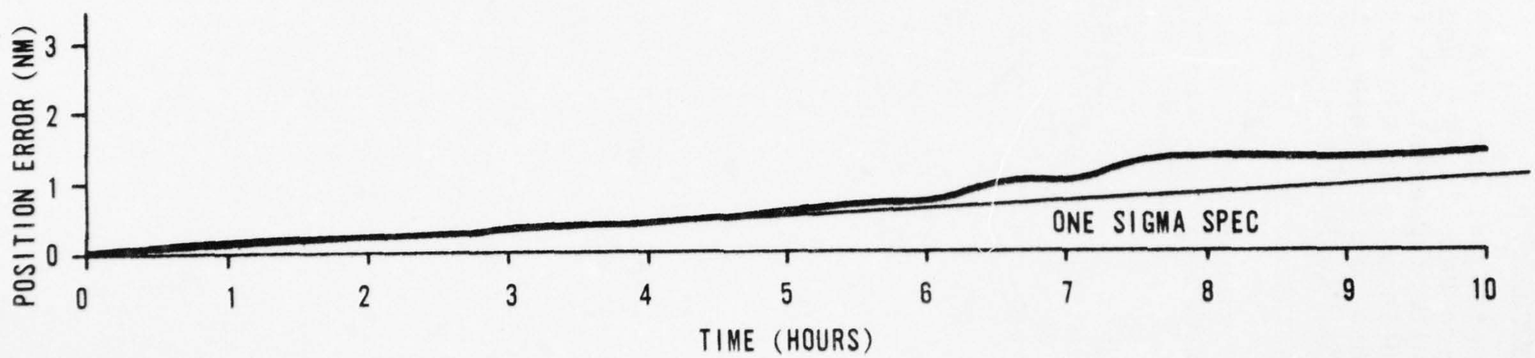


FIGURE 4

GEANS Flight Test Results

Extensive flight testing of the AN/ASN-101 (GEANS) was accomplished at Holloman Air Force Base in 1971 and 1972. The composite summary of flight test results represents thirty-three data flights in 1972 including operation in both an F4D and in a NC-135, and including high latitude flights out of Eielson Air Force Base, Alaska. Details of the testing appear in Reference C and D.

SUMMARY OF AN/ASN-101 (GEANS) HOLLOMAN FLIGHT TESTS

1179-08

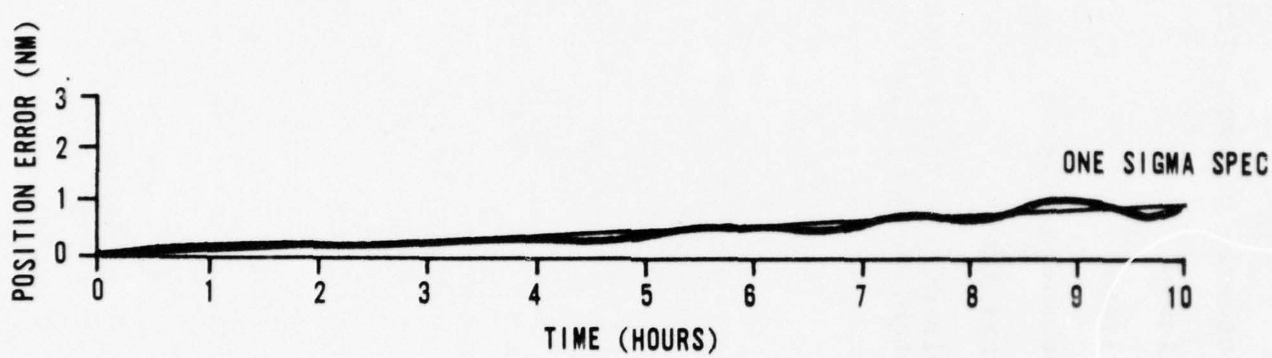


FIGURE 5

AN/ASN-101 (GEANS) F-4 Flight Test

The AN/ASN-101 (GEANS) was subjected to the following dynamic environments as a part of the F4D fighter test program at Holloman:

- Aerobatic Flight (rolls, chandelles, loops, immelmans, etc.)
- Clockwise rectangle pattern flights
- Z Pattern Flights
- Supersonic Flight
- Low Level, subsonic flights
- High speed taxi test

The maximum g levels during the fighter test program were +5.5 g's and -1.5 g's as established by limitations on the test aircraft.

AN/ASN-101 (GEANS) F-4 FLIGHT TEST

COMPOSITE OF EIGHT FLIGHT TESTS
JUNE 1972 THROUGH JULY 1972

1175-06

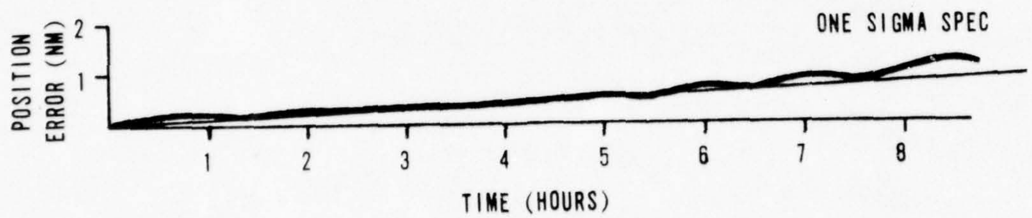


FIGURE 6

AN/ASN-101 (GEANS) High Latitude Flight Test

At the conclusion of the flight test activity, a series of high latitude exercises were conducted from Eielson Air Force Base, Alaska in August, 1972. The purpose was to evauate system performance at higher latitudes. Four pure inertial flights were made including a polar flyover.

AN/ASN-101 (GEANS)
HIGH LATITUDE FLIGHT TEST

COMPOSITE OF FOUR FLIGHTS
AUGUST 1972

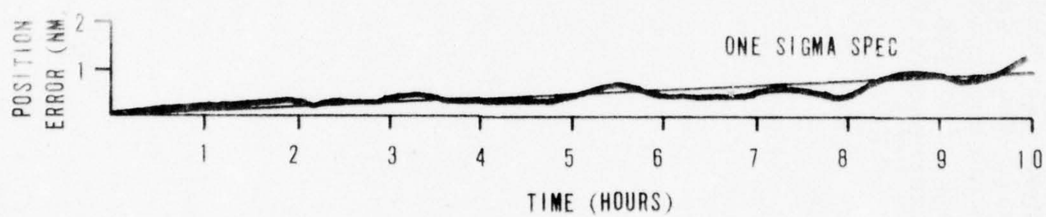


FIGURE 7

In Air Start/In Air Alignment

An optimization program was initiated following completion of the AN/ASN-101 (GEANS) flight testing previously described. The objectives were to remove limitations and design deficiencies uncovered during that testing. Provision of a "Zero Reaction Time" capability through implementation of air start/air align was a primary objective.

The optimized system was returned to Holloman AFB in 1974 for flight test in a C-141. In-air start was facilitated by use of the AHRS as an attitude reference during spinup. Velocity and position corrections were entered manually during the in-air alignment. The accompanying figure illustrates a representative test.

AN/ASN-101 DEMONSTRATED IN AIR START/IN AIR ALIGNMENT

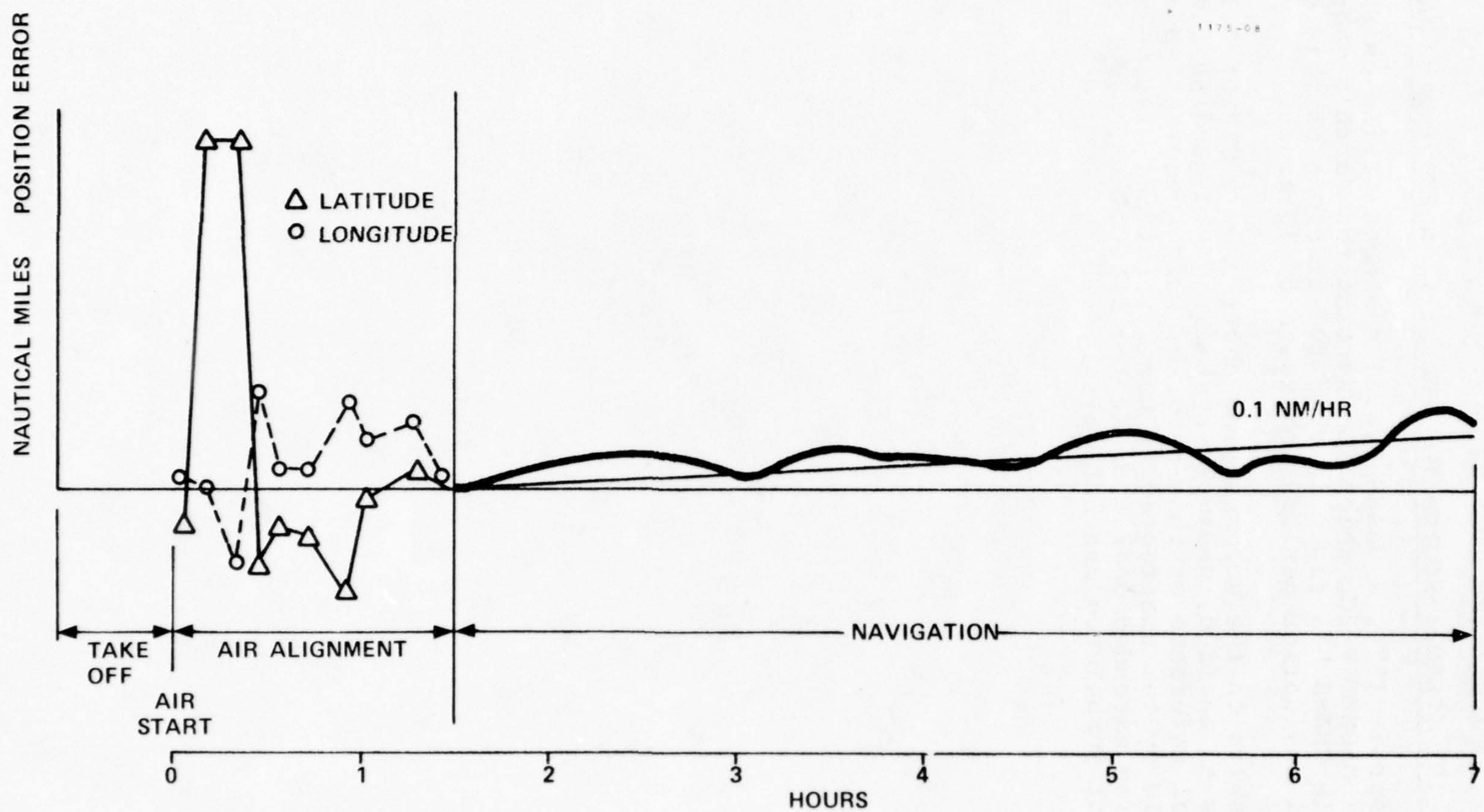


FIGURE 8

AN/ASN-101 (GEANS) System Test Results on Project Magnet

Since April, 1974, a GEANS System has been flying on NAVOCEANO's PROJECT MAGNET P-3C, which is charting the earth's magnetic fields. A single GEANS has flown in over 104 missions on this program with typical navigation periods in excess of 10 hours.

The results on the accompanying chart show a CEP of 0.13 nm/hr. This is an unaided, undamped system that is used as the primary inertial reference on this program, which requires an accurate and reliable system unaffected by the diversified mission scenario, including extended operation at low altitudes (<1,000 feet) with frequent turbulence and buffeting.

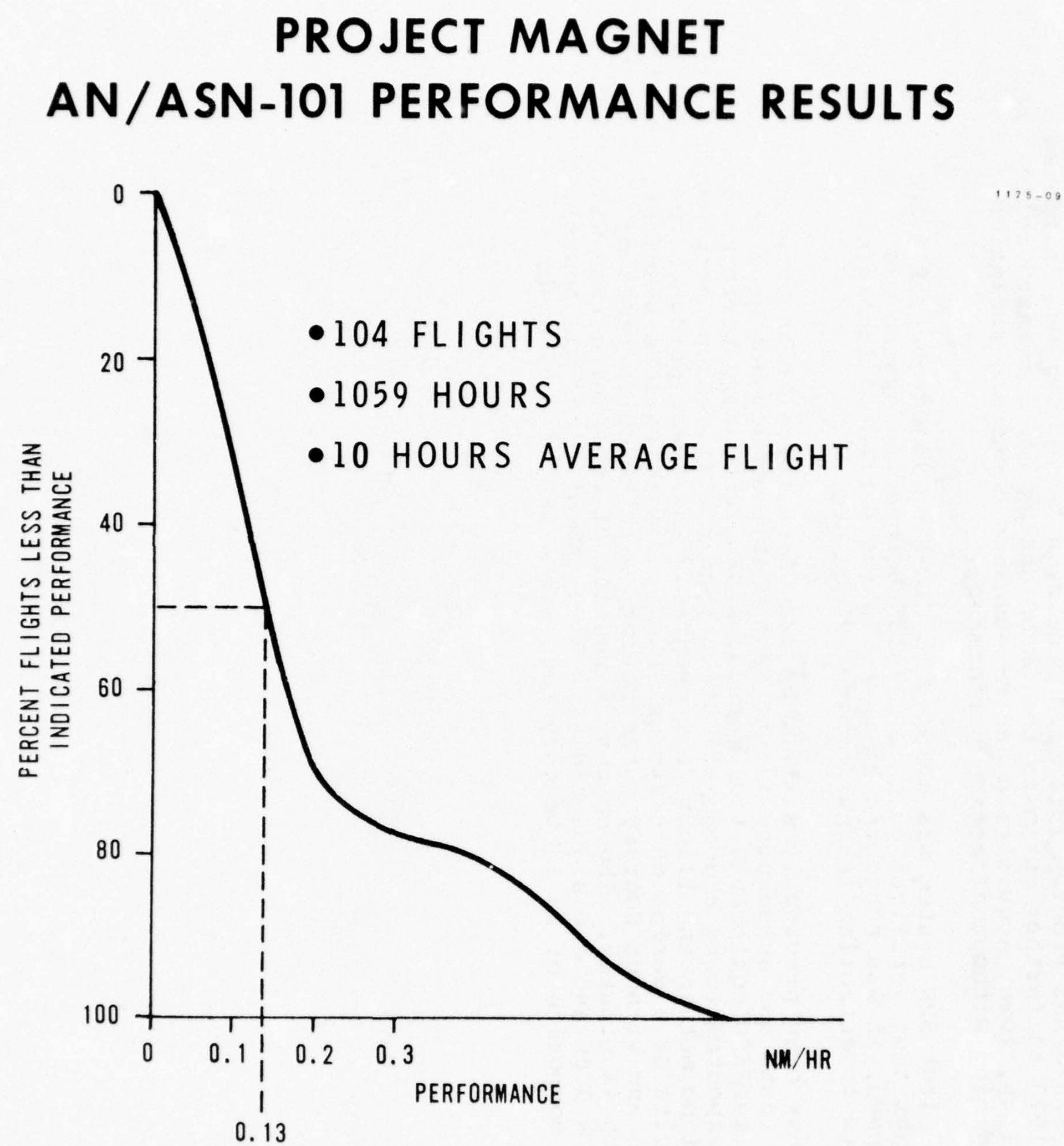

PROJECT MAGNET
AN/ASN-101 PERFORMANCE RESULTS
1175-09
•104 FLIGHTS
•1059 HOURS
•10 HOURS AVERAGE FLIGHT
PERCENT FLIGHTS LESS THAN INDICATED PERFORMANCE
0
20
40
60
80
100
0
0.1
0.2
0.3
0.13
NM/HR
PERFORMANCE

FIGURE 9

Results of SPN/GEANS Lab Tests

The SPN/GEANS Program (Standard Precision Navigator) was initiated in 1973 to further optimize the GEANS design for increased reliability, lower acquisition and maintenance costs and radiation hardening without affecting performance.

The first SPN System was shipped to CIGTF on 15 October 1975 for flight test verification on a C-141. Before the system was shipped, it was subjected to an extensive series of laboratory tests to establish its performance signature.

As has been previously stated, an excellent correlation between lab tests and subsequent flight tests has been demonstrated on earlier ESG equipment, therefore, the SPN laboratory performance is expected to be a good indication that specification performance will be met in the flight test program. The chart presents the results of a series of tests on SPN No. 2 with various headings, with and without Scorsby Table Motion, with reaction times of 31 to 43 minutes. The composite results of these nine runs was CEP = 0.06 and one sigma radial = 0.05 (nm/hr after six hours). The composite of 25 laboratory runs was a CEP of 0.05 nm/hr.

SPN/GEANS LAB TEST RESULTS
COMPOSITE OF NINE TESTS

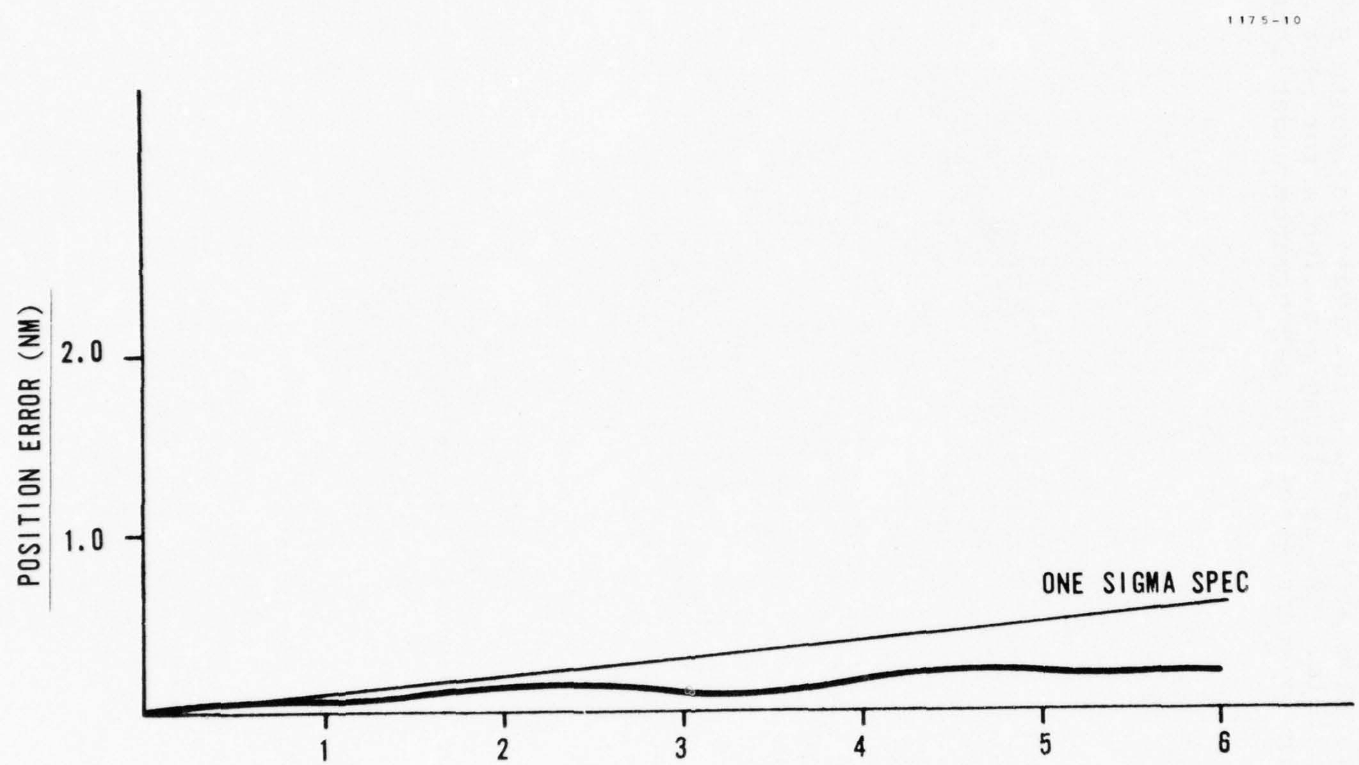


FIGURE 10

SPN/GEANS System No. 2 Lab Acceptance Test Run

This chart shows the actual acceptance test run position error plot for SPN System No. 2 before it was shipped to CIGTF. The length of the test was 12 hours with an RSS of 0.03 nm/hr with and without Scorsby Motion and with various heading changes. The heading changes were made at 42 minute intervals to excite Schulers as much as possible. The resulting position error plot clearly indicates the systems excellent performance under these conditions.

SPN/GEANS ACCEPTANCE TESTS

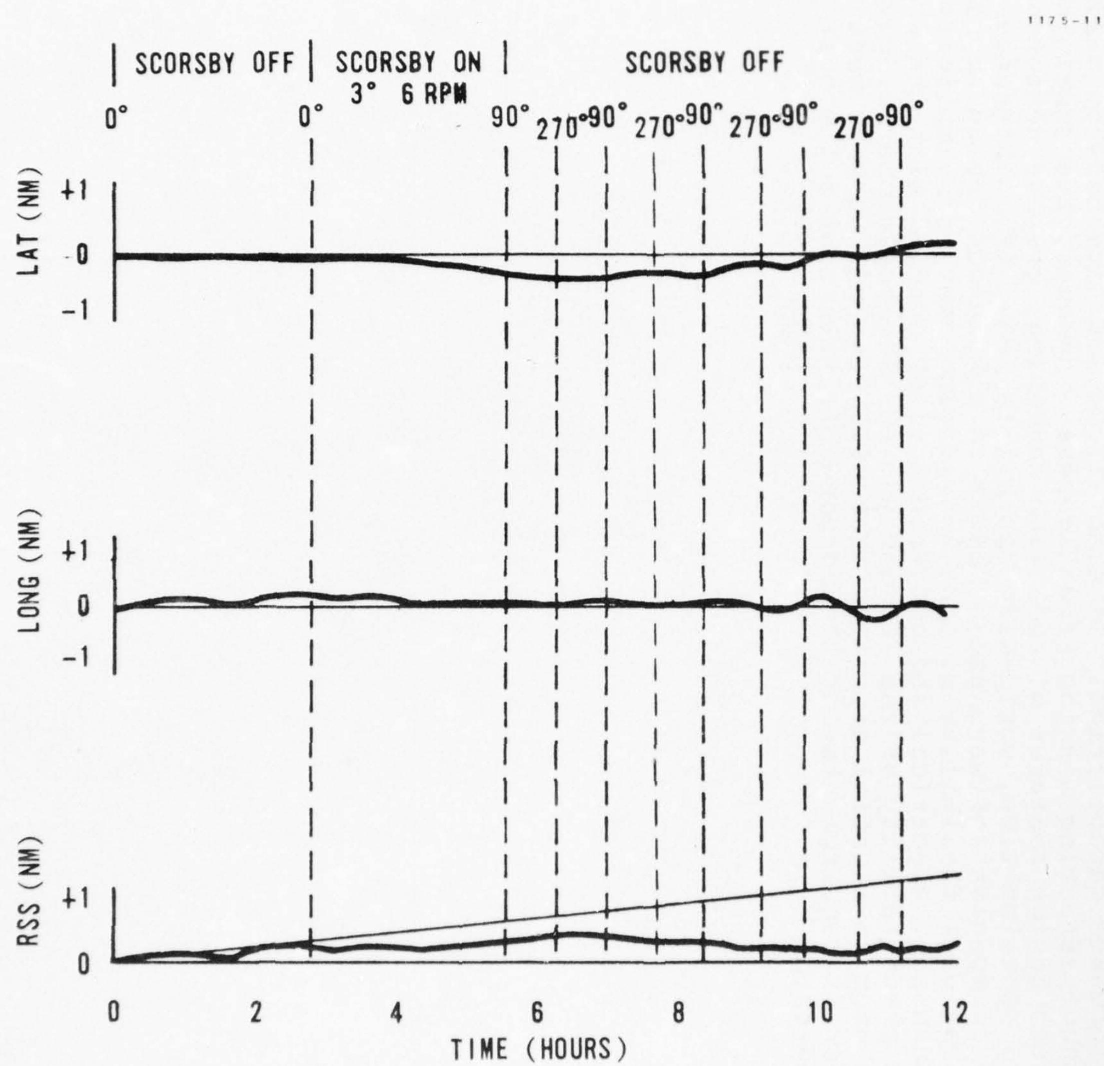


FIGURE 11

Operational Advantages of SPN/GEANS

The operational advantages of SPN/GEANS originate primarily from the inherent capabilities of the ESG, but not entirely. The ESG design permits SPN to operate during long missions with severe aircraft dynamics and no external aids and still achieve its inherent performance capabilities. It also allows 150 days between calibrations without affecting mission effectiveness. However, the remaining system design features of radiation hardening, precise sensor data, zero reaction time, world-wide capability, ease of maintenance and proven modular software are a result of a balanced design emphasizing operational flexibility without sacrificing cost and simplicity. The mechanical, electrical and software design, coupled with the accuracy and predictability of the ESG and the GG 177 accelerometer, give the user an inertial navigator that will meet and surpass most aircraft requirements for the foreseeable future at a low cost of ownership.

OPERATIONAL ADVANTAGES OF SPN/GEANS

1175-12

- Zero reaction time (Air Start/Air Align)
- No external aids required
- 150 day calibration interval
- World-wide capability
- Low sensitivity to aircraft dynamics
- Precise sensor alignment, stabilization and motion compensation
- Narrows operational corridor
- Nuclear hardened by design
- Modularized software

FIGURE 12

SPN/GEANS is Easily Maintainable by Air Force Field Level Personnel

From the inception of the GEANS Development Program, Maintainability and low Cost of Ownership have been part of the design and development requirements. Maintainability features and requirements were not only a function of the design process, but also complete support planning was included. The SPN/GEANS Program Office required constant review and validation of the design for maintenance as well as other design features. The maintainability characteristics have been proven in the field by the following examples:

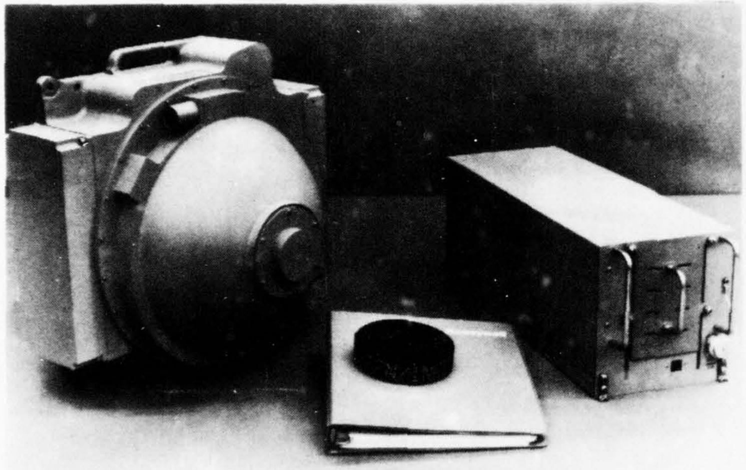
- Complete disassembly, repair and reassembly of the IMU gimbal assembly in less than eight hours by one technician.
- Replacement of gyro and VMUs at intermediate level in less than one hour excluding calibration.
- Achieved 0.2 maintenance hour per flight hour versus a requirement of 1.0 maintenance hour per flight hour for all levels of maintenance.

The accompanying chart shows the sequence of maintenance actions in replacing a VMU by using photographs of the system.

SPN/GEANS IS EASILY MAINTAINABLE

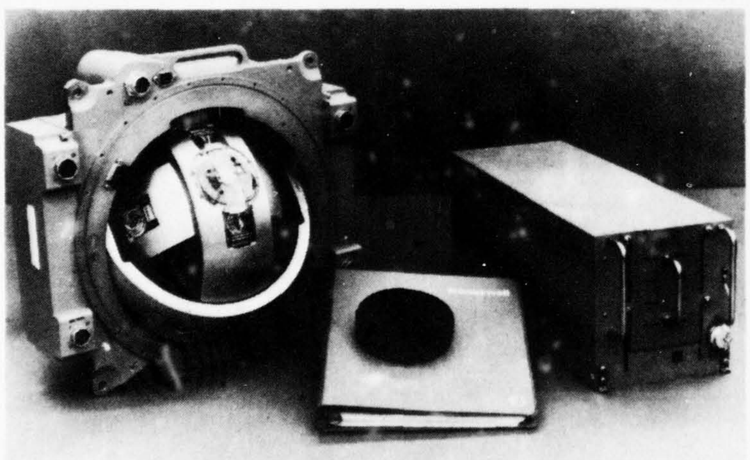
BY AIR FORCE FIELD LEVEL PERSONNEL

A7507-63



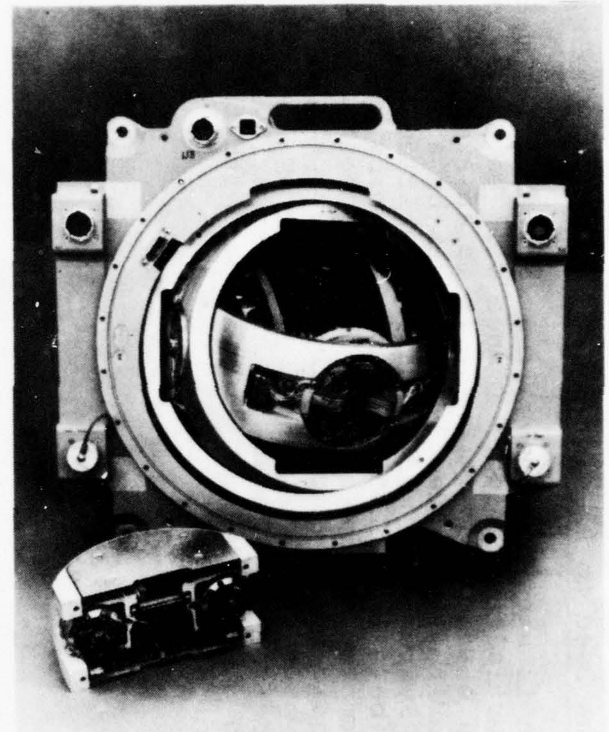
BITE ISOLATES THE FAILURE TO AN LRU

A7507-69



COVER IS EASILY REMOVED FROM IMU

A7507-60



VMU IS REPLACED BY REMOVING
FOUR SCREWS

FIGURE 13

Computer Simulations Used to Predict System Performance

Computer simulation is used by Honeywell as an effective means of predicting what inertial system performance will be under various dynamic, as well as static, conditions. It is an excellent tool to statistically verify the system error budget by adjusting parameter variations. System math models can be verified and, in fact, unknown models can be established. Vehicle dynamics are included so the expected performance of the system under a specific mission scenario can be predicted very accurately. The capability of the inertial system to perform missions such as missile initialization, weapon delivery, motion compensation, vehicle steering, etc., can be established with a high degree of confidence with this type of computer simulation.

COMPUTER SIMULATIONS USED TO PREDICT SYSTEM PERFORMANCE

1175-13

WHY USE SIMULATIONS?

- Statistically verifies system error budget
- Analyzes parameter sensitivities
- Verifies math models
- Predicts mission success
- Verifies computer algorithms

HOW ARE SIMULATIONS USED?

- Mechanize on-line software where possible
- Incorporate appropriate math models
- Define and implement external error sources
- Define and mechanize mission profile
- Establish initial conditions

WHICH ERROR SOURCES ARE INCLUDED?

- Initial conditions
- Inertial system
- Vehicle dynamics
- Earth model
- External systems

FIGURE 14

Simulation Example

The simulation used as an example of how the SPN system would perform in an operational environment is the classic strategic bomber mission. The system is in-air aligned while the aircraft is climbing to altitude, using doppler radar and position fixes every 15 minutes, with an accuracy of 1,600 feet CEP. The doppler is turned off for the period over water and turned on again at the landfall checkpoint where the aircraft has dropped to low level for penetration. During penetration there is automatic terrain following/terrain avoidance (TF/TA) with a significant g variation. There are also fixes every 30 minutes with the same accuracy as during in-air align. For comparison purposes the simulation shows what would happen if the doppler was not turned on and fixes were not obtained after landfall. Position CEP and velocity errors are plotted for both cases.

STRATEGIC BOMBER PERFORMANCE ANALYSIS WITH SPN/GEANS

- IN AIR ALIGN
- DOPPLER OVER LAND
- POSITION FIX = 1600 FT CEP

1175-16

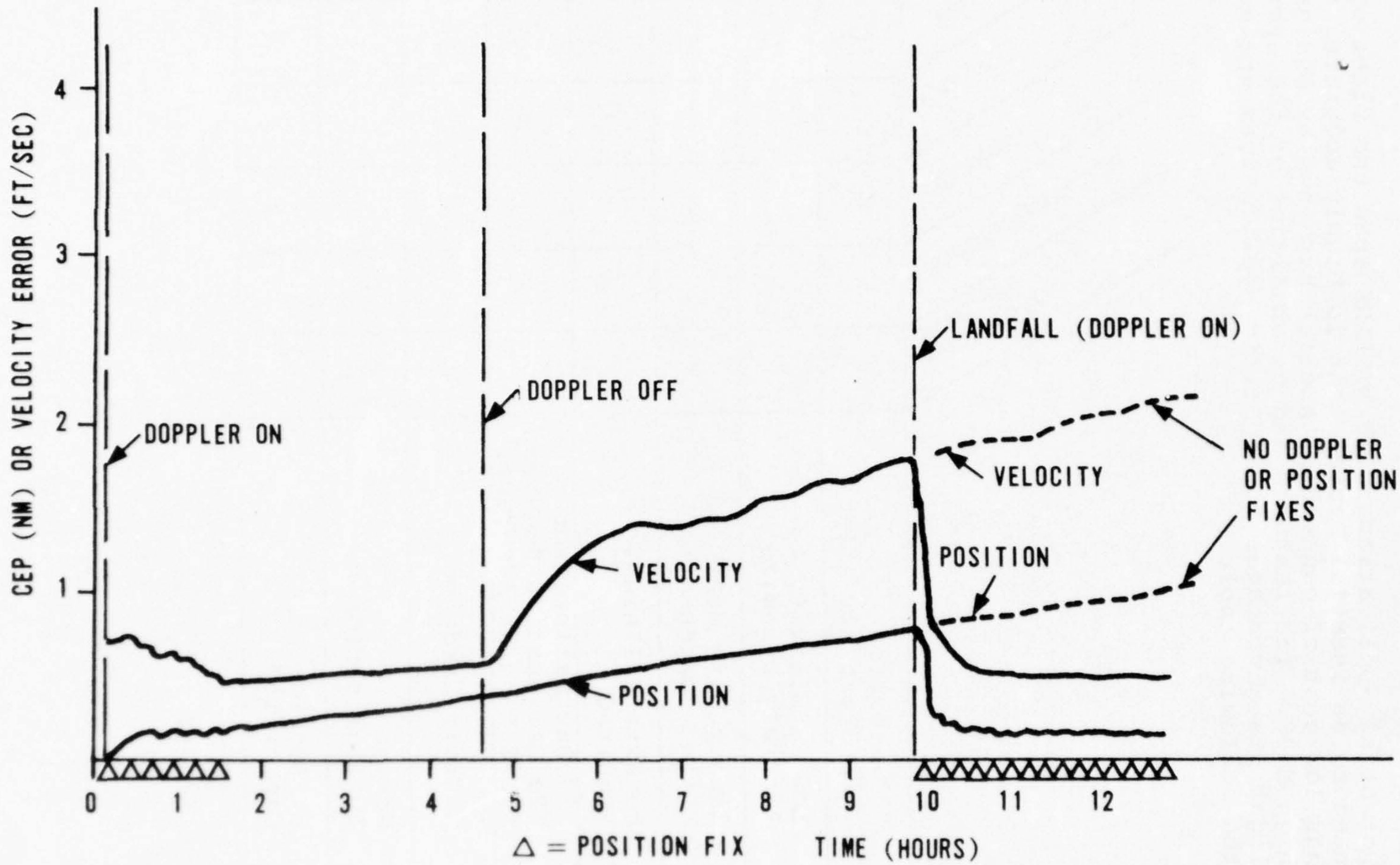


FIGURE 15

Application of SPN/GEANS

Potential applications of SPN/GEANS span the fleet of aircraft needing an inertial system that is highly accurate, maintainable, has low cost-of-ownership, nuclear hardened by design and has a high MTBF. The features and capabilities of the system that highlight its advantages for specific applications are easily shown in the following table.

	Strategic Bombers	Reconnaissance	Tanker	Cargo	ASW	Missile Carrier	Special Applications	
"0" Reaction (Air Start/Air Align)	✓	✓	✓		✓	✓	✓	
Low Sensitivity to Aircraft Dynamics	✓				✓		✓	
Sensor Alignment and Motion Compensation	✓	✓				✓	✓	
No External Aides Required	✓	✓	✓	✓	✓		✓	
150 Day Calibration (No Calibration Required for 0.5 nm/hr Accuracy)	✓	✓	✓	✓	✓	✓	✓	
Nuclear Hardened	✓		✓			✓	✓	
Weapon Initialization	✓					✓	✓	
World-wide Capability	✓	✓	✓	✓	✓	✓	✓	

APPLICATION OF SPN/GEANS

1175-15

- Strategic Bombers
- Reconnaissance
- Tankers
- Long-Range Cargo
- ASW
- Missile Carriers
- Special Applications

FIGURE 16

References:

A. Warzynski, R. R., "The Evolution of ESG Technology", NAECON '72 Record; Proceedings of the National Aerospace Electronic Conference, Dayton, Ohio, May 15-17, 1972. pp 56-63.

B. Ringo, R. L., "Cost-of-Ownership Design Philosophy for Inertial Navigators", Astronautics and Aeronautics, Vol II, June 1973, pp 59-63.

C. Sittloh, R. H., Flight Test of AN/ASN-101 Inertial Navigation System - Final Report, October 1972, AFAL-TR-72-350, DDC Number AD524341L.

D. Gniady, J., Newman, D., and Rooney, F., Final Report - Development Flight Test Gimbaled Electrically Suspended Aircraft Navigation System (GEANS) (U), November 1972, AFSWC-TR-72-33, Confidential, DDC Number AD523446L.

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

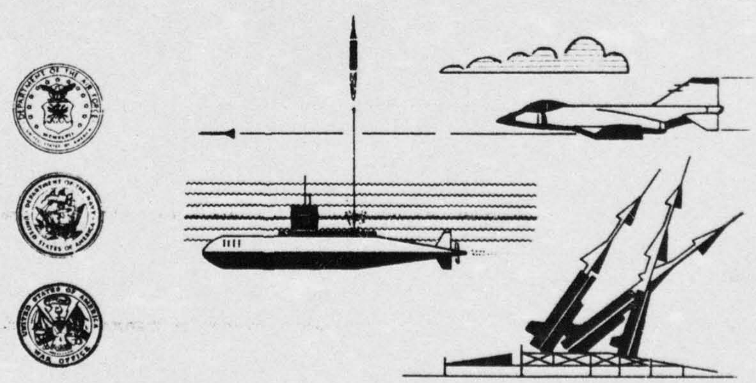
PLANNING GROUP

E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

LIFE CYCLE COST WORKSHOP

NOV. 18 – 19 1975

Joint Services Data Exchange Group for Inertial Systems



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and

HONEYWELL, AEROSPACE DIV.

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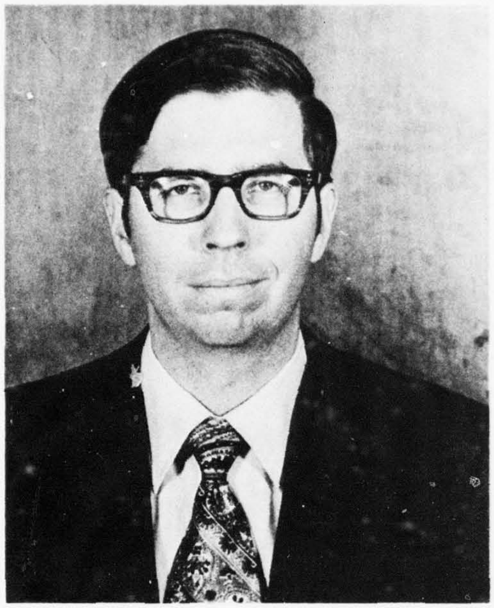
LIFE CYCLE COST WORKSHOP

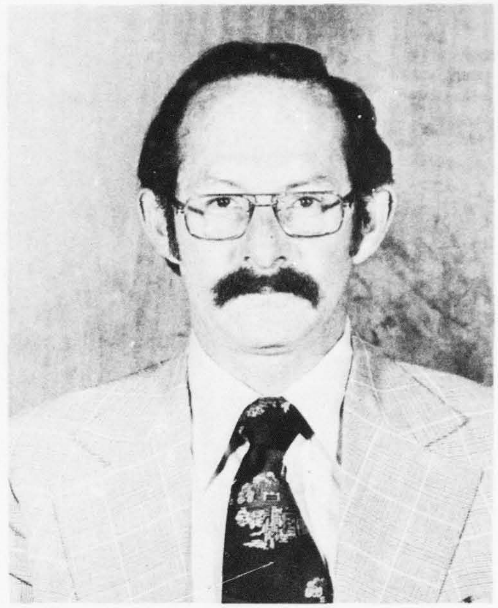
WORKSHOP CHAIRMAN

RUSSELL B. STAUFFER

Mr Stauffer recently retired from full-time service as Manager of the Tiras Department of Dynamics Research Corporation to form J & R Associates but maintains a close relationship with DRC as a part-time consultant, particularly in the area of Life Cycle Cost analysis. His major activity at the present time is in support of the DAIS Life Cycle Cost Program and is devoted to the development of techniques which will permit avionics systems designers to estimate the long-term operation and support cost effects of decisions made during conceptual design phase of new program development. Since August 1974, Mr Stauffer has been Chairman of the Life Cycle Cost Task Group of the Joint Services Data Exchange for Inertial Systems and has edited their quarterly proceedings. He is a graduate of Montclair State College and Rutgers University in New Jersey and has done additional graduate work in mathematics at Trinity College in Hartford, Connecticut.



DWIGHT COLLINS, LT
HQ AFLC



ROBERT ADEL
NORTHROP CORP

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LOGISTICS MANAGEMENT INSTITUTE

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AERONAUTICAL RADIO INC

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ROBERT C. DAY
LEAR SIEGLER

ANALYSIS OF DECISION CRITERIA FOR EXERCISING

RELIABILITY IMPROVEMENT WARRANTY OPTIONS

ON THE F-16 AIRCRAFT

PRESENTED BY

1/LT DWIGHT E. COLLINS

TO THE

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

18 NOVEMBER 1975

JOINT AFSC/AFLC COMMANDERS' WORKING GROUP ON

LIFE CYCLE COST

ASD/ACL

WPAFB, OHIO 45433

ANALYSIS OF DECISION CRITERIA FOR EXERCISING
RELIABILITY IMPROVEMENT WARRANTY OPTIONS
ON THE F-16 AIRCRAFT

The F-16 aircraft full scale development and production contract incorporated a variety of mechanisms for motivating the F-16 contractor to design features into the aircraft that would tend to reduce life cycle cost (see Chart 1). One of these is a contractual commitment to ensure that certain target levels of supportability are achieved by several aircraft subsystems that have historically been very costly to produce and maintain, e.g., the flight control computer, inertial navigation system, heads-up display, etc. This contract provision is called a Logistic Support Cost Commitment (LSCC) or Target Logistic Support Cost/Correction of Deficiencies (TLSC/COD) provision and it addresses thirteen such high cost items which are referred to in the contract as Control First Line Units (FLUs). It includes a TLSC which was established during contract negotiations using a simplified version of the Air Force Logistics Command's Logistic Support Cost (LSC) Model as a framework for cost accumulation. It calls for a 3500 flying hour verification test beginning six months after Initial Operational Capability (IOC) is established. During this test, LSC model parameter estimates will be updated and a Measured Logistics Support Cost (MLSC) will be computed. If the MLSC is less than the TLSC, the contractor will be eligible for an award fee under the LSCC whereas, if the MLSC exceeds the TLSC by more than 25%, a correction of deficiencies (COD) program will be undertaken.

The contract also allows for the Air Force to exercise an option to purchase either a fixed price four year Reliability Improvement Warranty (RIW) or an RIW with MTBF guarantee (RIW/MTBF) in place of the LSCC for any number of the control FLUs. Under the RIW, the contractor can increase his profit by improving equipment reliability. The RIW includes a remedy from the contractor for slow repair turnaround time in the form of a requirement to provide additional spare FLUs at no cost to the Air Force. The RIW/MTBF is similar to the RIW except it includes a series of MTBF targets which must be met over the four year period. Its initial fixed price is larger than that of the RIW in order to compensate the contractor for assuming the additional risk of failure to meet these guaranteed MTBFs.

Finally, the contract includes ceiling prices for both an RIW and an RIW/MTBF at the module level. Actual prices for both these latter warranty options were not negotiated during F-16 full scale development - production contract negotiations because the control FLU modules were not sufficiently defined at that time. Hence, for each control FLU, the Air Force can consider any one of five contractual mechanisms as a means of controlling F-16 logistics support costs: LSCC, RIW, RIW/MTBF, RIW

CONTRACT ALTERNATIVES

CONTROL FIRST LINE UNITS (FLUs)

TLSC/COD

- CONTRACTOR BID PARAMETERS - TLSC
- VERIFICATION TEST - MLSC
- COD PROGRAM IF MLSC > 125% TLSC
- AWARD FEE IF MLSC < TLSC

LSC MODEL

RIW

- 4 YEAR FIXED PRICE REPAIR CONTRACT
- GREATER PROFIT BY IMPROVING RELIABILITY
- REMEDIES FOR SLOW REPAIR TURNAROUND

RIW/MTBF GUARANTEE

- LARGER FIXED PRICE FOR MTBF GUARANTEE
- REMEDIES FOR FAILURE TO MEET GUARANTEED MTBFs

RIW AND RIW/MTBF AT MODULE LEVEL

CHART 1.

at the module level, and RIW/MTBF at the module level. The Air Force must decide which of these options to exercise for each control FLU prior to the initiation of F-16 production (January 1977). This set of decisions will have a significant impact both on Air Force costs and on F-16 mission reliability. In the remainder of this paper, a methodology recently developed at the Air Force Institute of Technology (AFIT) for analyzing these decisions in terms of their impact on cost and mission reliability is presented.[1]

Air Force Costs Under the Logistic Support Cost Commitment

The first stage of the methodology essentially consists of a sample analysis of total variable costs to the Air Force of each of the first three decision alternatives (LSCC, RIW, and RIW/MTBF).[2] Chart 2 summarizes the three key types of Air Force cost under the LSCC: First, there is FLU-related logistic support cost. The three dominant elements of this cost (initial and replacement spares costs, on-equipment maintenance costs, and off-equipment maintenance costs) are estimated using the first three equations of the modified AFLC LSC Model. A lifetime of 15 years is assumed. The monthly peak force flying hours (PFFH) used in the computation of spares costs is currently projected to be achieved during the fifth year after production begins.

The second primary type of cost incurred under the LSCC is related to contractor performance. First, there is a COD target price. This is a negotiated dollar amount for each control FLU which will be paid by the Air Force for technical risks assumed by the contractor under the LSCC. Second, there may be costs connected with COD modification. Namely, if the COD provision is invoked and the contractor is required to remedy supportability-related equipment problems, a portion of the costs of these remedies may be incurred by the Air Force depending on the magnitude of other contractor costs under the incentive sharing arrangement of the production contract.

---

1. This methodology was developed in the following two Masters thesis efforts at the AFIT School of Engineering (Department of Systems Management (AFIT/ENS)):

   a. Capt T. Koegel and Capt N. Mills, "An Analysis of Decision Criteria for the Selection of F-16 Reliability Improvement Incentive Alternatives," Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 45433, June 1975.

   b. Capt A. Doman and Capt A. Dunkerley, "Evaluation of F-16 Subsystem Options Through the Use of Mission Completion Success Probability and Designing to System Performance/Cost Models," Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 45433, September 1975.

Both thesis efforts were conducted under the direction of Major Robert Tripp of AFIT/ENS and the author.

2. The methodology does not explicitly treat the module level RIWs because module data was not yet available when methodology development was undertaken.

TLSC/COD COST ANALYSIS

15 YEAR LOGISTIC SUPPORT COSTS

- SPARES
  - PFFH IN 15 YEAR LIFETIME
- ON EQUIPMENT MAINTENANCE
- OFF EQUIPMENT MAINTENANCE

TLSC/COD PERFORMANCE

- BASIC TARGET PRICE - CONTRACTOR BID
- COD MODIFICATION

TLSC/COD AWARD FEE

- $2,000,000 FOR ALL CONTROL FLUs
- FLU SHARE PROPORTIONAL TO TOTAL TLSC CONTRIBUTION

CHART 2

The third key type of cost to the Air Force under the LSCC is an award fee for which the contractor becomes eligible if the MLSC during the 3500 hour verification test is less than the TLSC. The total amount of this fee for all thirteen control FLUs is $2M.

Air Force Costs Under the Reliability Improvement Warranty

Air Force costs under the RIW comprise three main elements (see Chart 3). First, the negotiated fixed price of the RIW covers the estimated cost of contractor repair of all FLU failures during the four year warranty period. It also reflects consideration of profit and the risk of higher than expected contractor costs due to poor equipment performance in the field. An advantage of the RIW is that the contractor has considerable control over the repair process. Namely, he can modify his equipment as it passes through his repair facility to increase its reliability in the field, thereby decreasing the frequency of subsequent returns to his facility and, hence, his subsequent repair costs.

The second major RIW cost is the cost of FLU spares. The methodology also uses the spares equation from the AFLC LSC Model to compute this figure. Although the PFFH/month figure used here is less than under the LSCC (PFFH at the four year point as opposed to PFFH after all production aircraft have been fielded), cost of initial pipeline spares is very much higher because of 100% depot (contractor) repair under the RIW as opposed to less than 10% under the LSCC.

The final major cost elements under the RIW are the costs of on-equipment and off-equipment FLU maintenance during the eleven years of aircraft life after the four year RIW period. Appropriate AFLC LSC Model equations are used to compute these costs also. An interesting property of the RIW is that the number of spare FLUs required during the four year RIW period is much more than adequate to support the equipment under the organic maintenance concept during the remainder of its life. One possibility that arises here is that some of these excess spares can be installed on new aircraft during the fifth year of production, thereby decreasing effective RIW costs to the Air Force. This possibility is currently being investigated by the Air Force.

Air Force Costs Under the RIW/MTBF

The structure of costs to the Air Force under the RIW/MTBF is very similar to the RIW cost structure (see Chart 4). Besides a greater initial fixed price to cover increased risk to the contractor as noted earlier, the main difference in cost structure lies in the area of spares. Under the RIW/MTBF, a low MTBF in the field can result in a greater requirement for the contractor to provide consignment spares than under the regular RIW. If this low MTBF persists through the four year point, these consignment spares become the property of the Air Force, thus reducing total costs to the Air Force more than would occur in the case of the RIW under similar conditions.

RIW COST ANALYSIS

RIW FIXED PRICE - CONTRACTOR BID

SPARES

- 100% DEPOT REPAIR CONCEPT
- PFFH IN 4 YEAR WARRANTY PERIOD
- EXCESS SPARES USED ON NEW PRODUCTION AIRCRAFT

11 YEAR MAINTENANCE

- ON EQUIPMENT
- OFF EQUIPMENT

CHART 3

RIW/MTBF GUARANTEE COST ANALYSIS

RIW/MTBF GUARANTEE FIXED PRICE

- CONTRACTOR BID

SPARES

- BASIC RIW
- CONTRACTOR PROVIDED CONSIGNMENT SPARES

11 YEAR MAINTENANCE

- BASIC RIW

CHART 4

Costs Ignored by the AFIT Methodology

The AFIT methodology ignores several traditional elements of cost in its analysis of the various control FLU decision alternatives (see Chart 5). In many cases this is done in the interest of simplicity and can be easily justified. For example, it is anticipated that R&D and unit production costs will not vary from one decision alternative to the next and, hence, need not be addressed. The methodology developers argue that three classical elements of logistic support cost, namely, cost of inventory entry and supply management, cost of personnel training and training equipment, and cost of management and technical data, are similar enough for all the decision alternatives to be justifiably ignored in the interests of simplicity. The methodology excludes consideration of the cost of support equipment (SE) because there is no requirement for SE peculiar to control FLUs only. Additional elements of costs that are relatively small in size such as the cost of removing and replacing failed FLUs on the aircraft under the RIW are also ignored. However, two potentially significant elements of cost, namely, cost of stockage and repair of FLU lower level assemblies and cost of packaging and shipping, are not addressed by the methodology because there was no available data in these areas during the period of methodology development. Any future update of the methodology should attempt to address these cost elements.

The Mission Reliability Methodology

In addition to cost, the AFIT methodology incorporates a capability to examine the impact of the control FLU decision alternatives on mission reliability. The first step in this computation is the calculation of the aircraft mission reliability as measured by mission completion success probability (MCSP). This is done using an MCSP model developed in recent years at Kirtland AFB (see Chart 6).[3] This model requires three types of input information: (1) a description of the aircraft mission profile, i.e., the lengths of each of the mission phases, (2) an estimate of the MTBF expected to be achieved in the steady state under each of the three decision alternatives for each of the control FLUs, and (3) an estimate of the conditional probability of an aircraft abort given a FLU failure for each of the control FLUs and each of the mission phases. The main purpose of these conditional abort probabilities is to reflect differing degrees of criticality with respect to mission success from one FLU to the next.

The MCSP model provides three kinds of output information. First, it ranks the set of FLUs being examined in terms of probability of causing an aircraft mission abort. Second, it can provide an analysis of sensitivity of the aircraft MCSP to changes in one or more of the FLU MTBFs. Finally, it computes the aircraft MCSP that results from a given combination

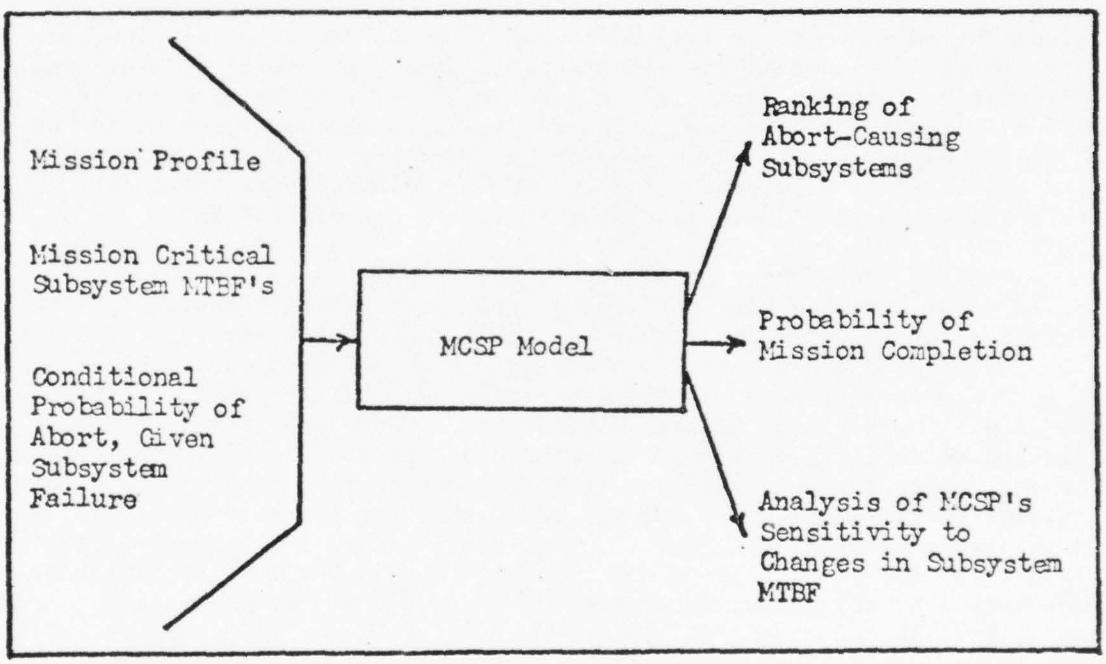
---

3. This model is described in detail in "Models and Methodology for Life Cycle Cost and Test and Evaluation Analyses" (OAS-TR-73-6), by R.H. Anderson et al, Directorate of Aerospace Studies, DCS/Development Plans, Air Force Systems Command, Kirtland AFB, New Mexico, 87117, July 1973 (DDC #AD782182).

EXCLUDED COSTS

R&D →	SUNK
UNIT PRODUCTION PRICE →	SUNK
INVENTORY ENTRY AND SUPPLY MANAGEMENT →	RELATIVELY SMALL, SIMILAR FOR ALL 3 ALTERNATIVES
PERSONNEL TRAINING AND TRAINING EQUIPMENT →	
MANAGEMENT, TECH DATA →	
AGE →	NO CONTROL FLU PECULIAR AGE
REMOVE & REPLACE (RIW) →	RELATIVELY INSIGNIFICANT
STOCKAGE & REPAIR OF FLU LOWER LEVEL ASSEMBLIES →	UNKNOWN, BUT POTENTIALLY SIGNIFICANT
PACKAGING & SHIPPING →	

CHART 5



Input-Output Diagram for an MCSP Model

Chart 6

of decision alternatives on the control FLUs, e.g., (1) RIW on the flight control computer, (2) TLSC/COD on the inertial navigation system, (3) RIW/MTBF on the heads-up display, (4) similarly on FLUs 4 through 13. In general, a change in decision alternative for one or more FLUs, e.g., going from an RIW to an RIW/MTBF on the flight control computer, would result in a different aircraft MCSP which could easily be computed by the MCSP model.

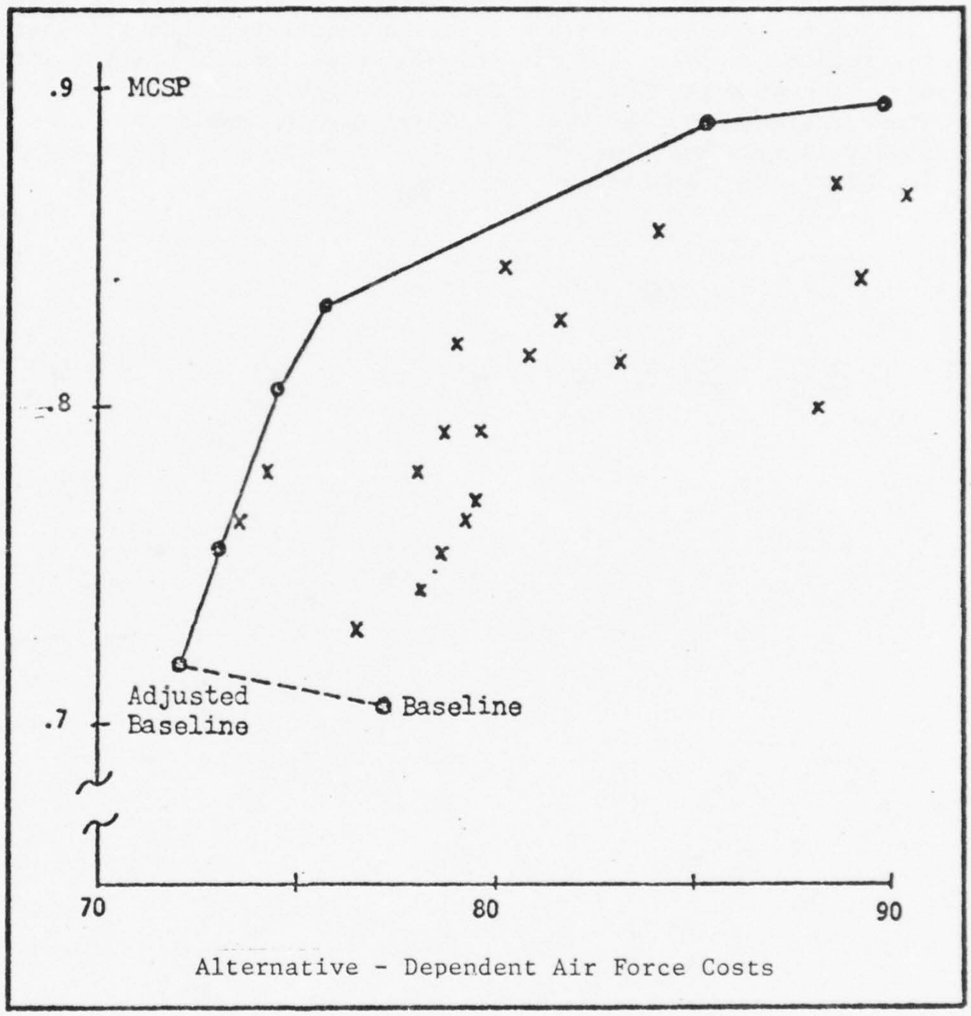
The next stage of the AFIT methodology combines both the cost and mission reliability information examined so far. An optimization procedure is used to determine that combination of control FLU decision alternatives which results in a maximum MCSP for any given expenditure of alternative dependent Air Force costs.[4] Chart 7 provides a conceptual picture of this process. The horizontal axis measures cost and the vertical axis measures MCSP. Each X represents some combination of control FLU decision alternatives in terms of its impact on these two parameters.[5] The baseline point, computed by the procedure, is that combination of decision alternatives which results in a minimum MCSP. The adjusted baseline point, also computed by the procedure, is the least cost combination of decision alternatives. Each consecutive vertex point on the concave piecewise linear curve that connects to the adjusted baseline point reflects a change of decision alternative for one control FLU.

Clearly, this curve provides the decision maker with a means of discriminating among alternatives. He may simply be interested in that set of alternatives which results in least cost to the Air Force. If so, the methodology determines the unique combination of alternatives that has this attribute, namely, the adjusted baseline point. Or perhaps he is willing to incur additional costs to achieve a higher aircraft mission reliability. If so, the methodology provides him with an estimate of the unique maximum mission reliability combination of decision alternatives that is achievable for any additional Air Force expenditure. Or maybe he is interested in a particular combination of alternatives that lies below the concave curve but reflects certain qualitative attributes not shared by any of the maximum MCSP combinations. For example, perhaps he is inclined to choose the TLSC/COD alternative for all 13 control FLUs mainly because he feels it is important to maintain the higher level of Air Force self sufficiency reflected by organic maintenance as opposed to contractor maintenance under either type of RIW. If so, computation of the concave curve of maximum MCSP combinations provides him with an estimate of how much he is sacrificing in terms of cost and mission reliability in choosing this combination of alternatives. A variety of additional tradeoffs that confront the decision maker can be explicitly characterized through computation of the maximum MCSP curve.

---

4. This optimization procedure was also developed at Kirtland AFB and is described in the document referred to in footnote 3.

5. If there are n FLUs (in this case, 13) being considered and m decision alternatives for each FLU (in this case, 3), the number of these possible combinations is m^n (or $3^{13} = 1,594,323$).



Optimal DSPC Curve

Chart 7

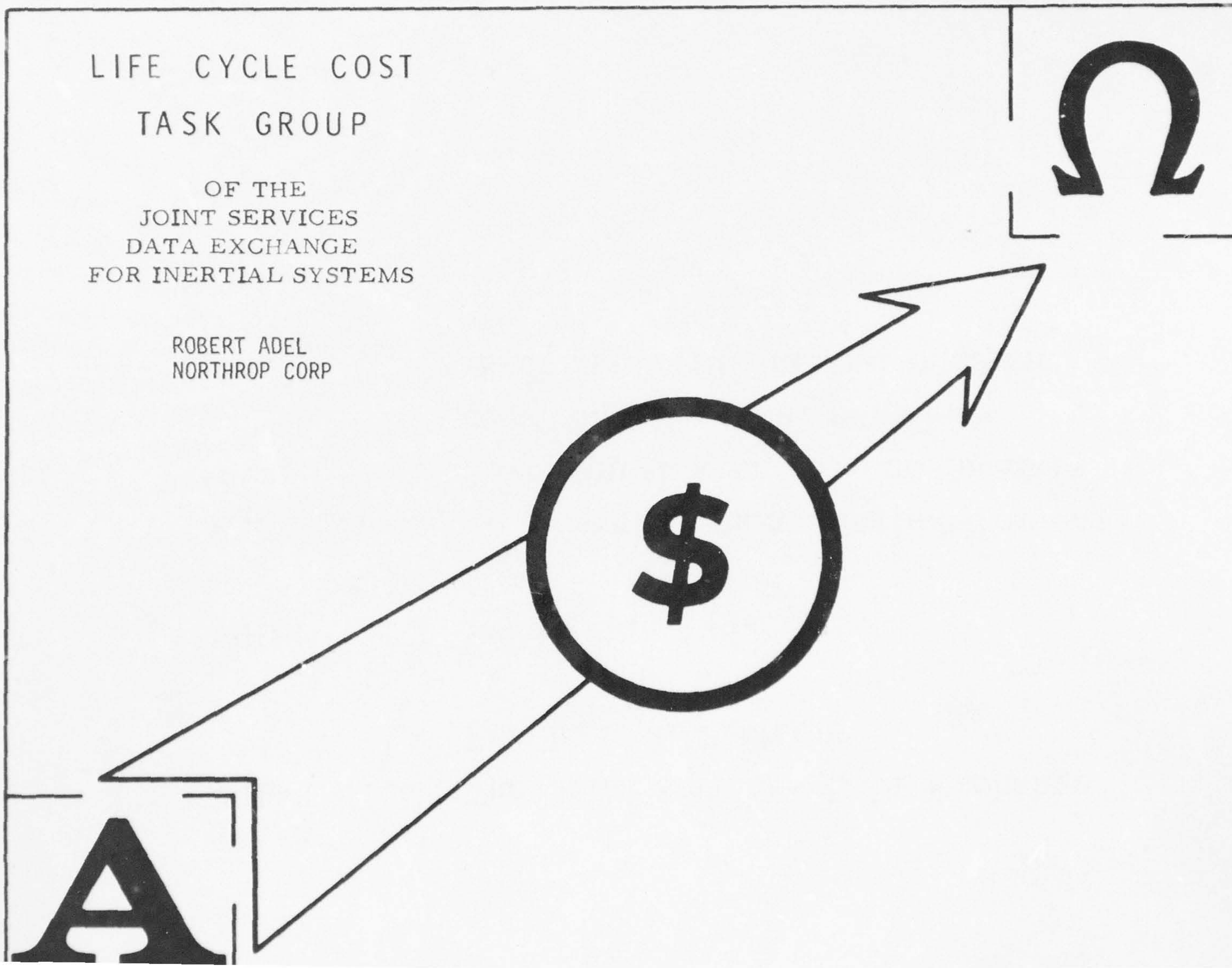
Summary

In the near future, the Air Force will have to decide whether to exercise warranty options on each of several F-16 control first line units. This paper has briefly described a methodology recently developed by four students in the AFIT School of Engineering for analyzing the impact of this set of decisions on total cost to the Air Force and F-16 mission reliability. This work has demonstrated that this set of decisions is, indeed, complex. It has provided considerable insight into a variety of different ways that these decisions impact cost and mission reliability. These insights should be utilized along with consideration of decision impact in such qualitative areas as Air Force self sufficiency when the decisions are actually made.

LIFE CYCLE COST TASK GROUP

OF THE
JOINT SERVICES
DATA EXCHANGE
FOR INERTIAL SYSTEMS

ROBERT ADEL
NORTHROP CORP



WHAT .... The Joint Services Data Exchange For Inertial Systems

WHEN .... Founded in 1969

WHY .... To improve communications among Government agencies and industry regarding technical problems associated with inertial systems.

INERTIAL SYSTEM COST ASPECTS ARE A MAJOR CONSIDERATION

August, 1973

Results of a JSDE special committee meeting

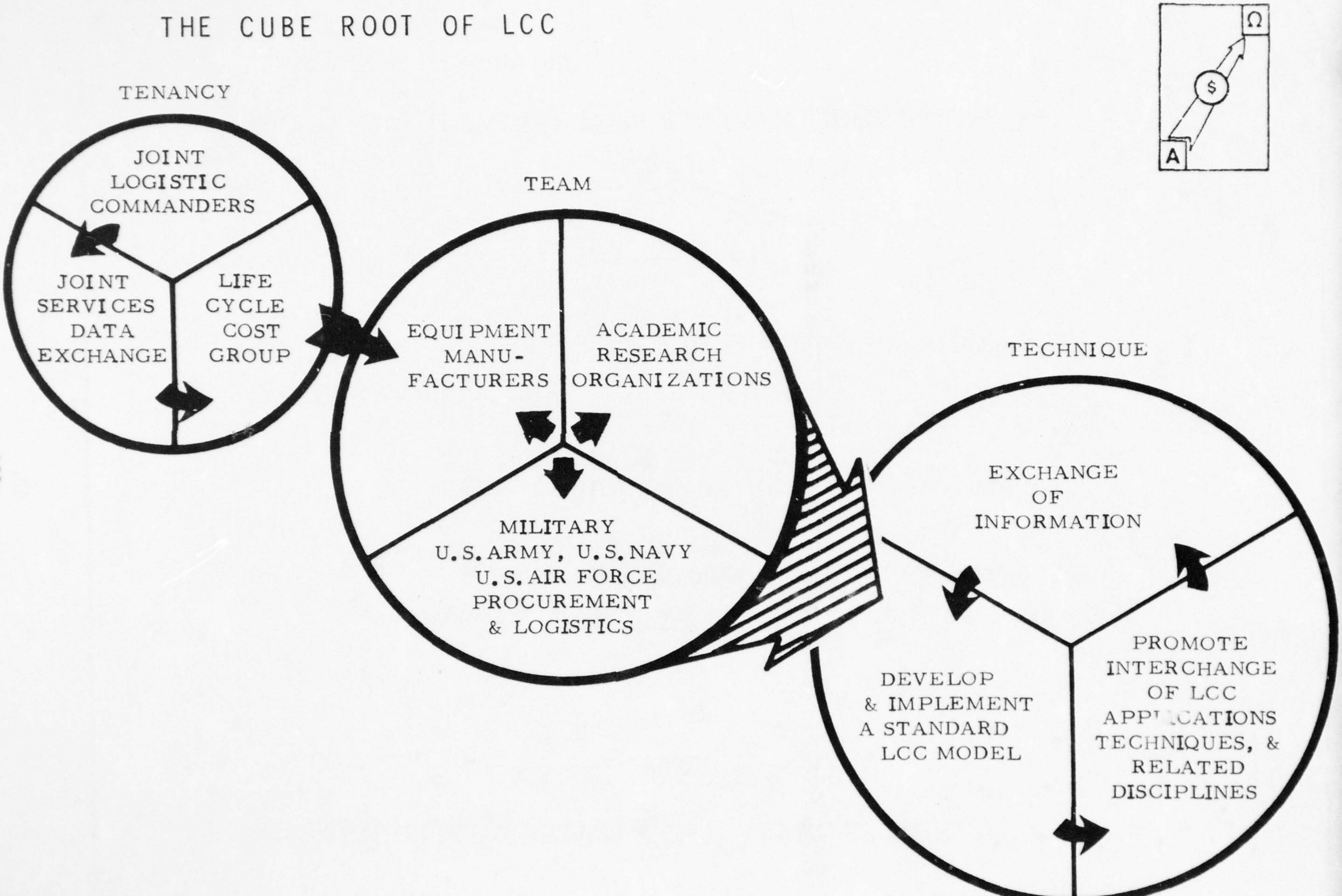
- Basic definitions of cost parameters could not be established
- A multiplicity of analytical approaches was apparent

Outgrowth

Organize a formal, objective-oriented study group

LIFE CYCLE COST TASK GROUP

THE CUBE ROOT OF LCC



LCC TASK GROUP OPERATION

EXECUTIVE COMMITTEE

2 Members from the Government

2 Members from Industry

2 Members from Academic/Research

- Elect two committee members as task group chairman and vice-chairman
- Establish agendas for the quarterly meetings
- Schedule speakers
- Coordinate interim work assignments of the general members

Meetings are divided equally between:

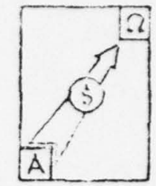
Presentation of papers

Working sessions to prepare and implement a standard model

MEMBERSHIP IS OPEN TO ANYONE INTERESTED

MILESTONES IN THE LCC TASK GROUP ACTIVITIES

Jan, 1974	Numerous LCC models presented and discussed. Working models distributed to members.
Apr, 1974	Divided into working parties to identify the requirements for a standard model.
Jun, 1974	Developed algorithms to mathematically express the life cycle cost incurred during RDT&E, Acquisition, and O&M.
Aug, 1974	Task group meeting was held in conjunction with the 8th annual meeting of the parent group. Continued compilation of the model algorithms.
Nov, 1974	Model input requirements and output formats were defined.
Feb, 1975	Ambiguities and duplications in the algorithms were identified and eliminated. Input and output formats were finalized. Computer programming began.
Jul, 1975	Worked specific problem areas related to programming the model. Began preliminary assignments for preparation of a User's Manual.
Nov, 1975	(Scheduled) Programming to be complete and ready for initial debugging and testing. Rough draft of User's Manual to be 60% complete.



INTERCHANGE VEHICLES

PAPERS
- Department of Defense
- Senior Military Commands
- Key Industrial Personnel

TOPICS
- Existing LCC Models
- Development of Cost Estimating Relationships
- Application of LCC

PRESENTORS
- John D. S. Gibson, ASD/ACL
- W. L. Smith, HQ USAF/LGPLA
- Brig. Gen. Robert Duffy (Ret), CSDL
- Harold S. Balaban, ARINC
- Russell Shorey, ODDR&E

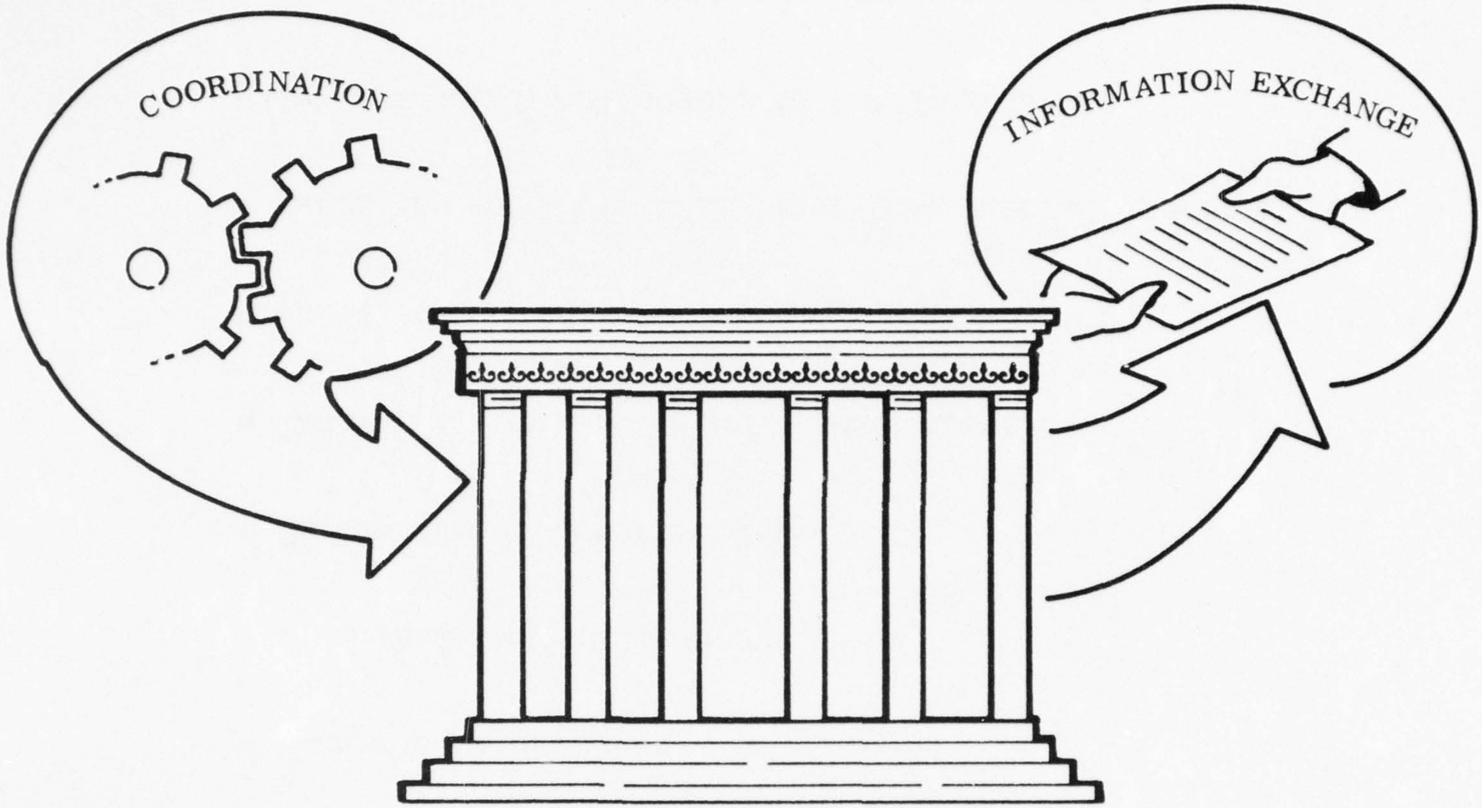
LCC MODEL CHARACTERISTICS

- Basic Accounting Model
- Flexible - May be used by Military, Industry, Research
- Can predict LCC at any phase of the program
- Provides for input data at any level
- Creates a data file - User may create any output format he desires (in addition to "standard" formats)
- "Fixed" parameters can be readily replaced or modified

IT IS PLANNED TO DEBUG THE PROGRAM, RUN SENSITIVITY TESTS, AND COMPARE THE MODEL WITH OTHER MODELS IN 1976.

FUTURE PLANS

- Continue to interchange information
- Publish the standard model
- Standardize Government inputs
- Establish a procedure for change control
- Complete the User's Manual
- Adapt the model to uses other than inertial systems
- Interest additional people in the Task Group
- Pass the Group's experience and knowledge to others



☆ LCC FORUM

PART II

"BOTH THE ANNUAL FUNDING
APPROACH AND OUR GENERAL
CONCERN FOR CURRENT
BUDGETS MAKE NEAR-TERM
COST TRADE-OFFS FOR FUTURE
SAVINGS DIFFICULT."

NORTHROP
Electronics Division

SLIDE 1

In general, warranty, LCC and DTC programs are publicized by DOD and the Military as "dollar saving", "everyone wins" new concepts in contracting. Everyone is eager to cite the examples that defend this position. No one talks about the losers -- and so far there are probably few, if any, contractors or service agencies who have actually lost. But, the concepts are very new and though more and more contracts are being awarded with warranty, LCC or DTC clauses, there has not been sufficient time to determine if all have been profitable or not.

In time, there most certainly will be some losers. We all hope that they will be far outnumbered by winners, but, unless everyone concerned understands the pitfalls, the possibility of an unpleasant outcome exists. This statement (reference to Slide 1) was made by the Assistant Secretary of the Air Force for Systems and Logistics, Mr. Frank Shrontz. I think what he is saying is that it is difficult for the contractor to swallow the concept that the military source selection team will award a contract to a company that may not be the lowest bidder but promises future savings. It is a normal attitude to be most concerned about the near term budget -- especially with the current dollar squeeze.

PAY THE PRICE

IT COSTS MORE TO:

1. Write RFP's
2. Prepare proposals
3. Provide additional data
4. Provide contract administration
5. Manage the contract
6. Negotiate changes

NORTHROP
Electronics Division

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DATA EXCHANGE FOR INERTIAL SYSTEMS (9TH), CONFERENCE PROCEEDING--ETC(U)
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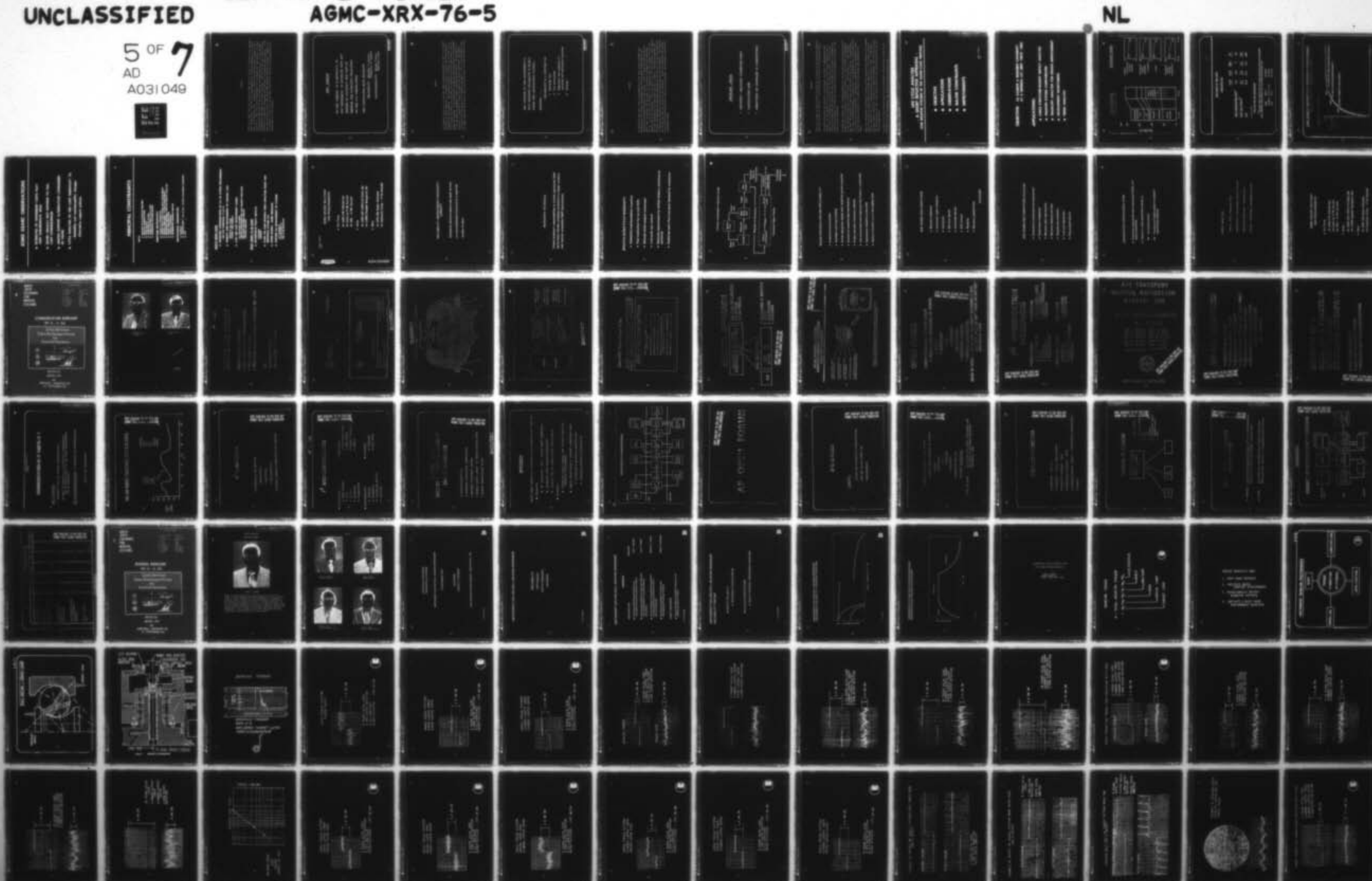

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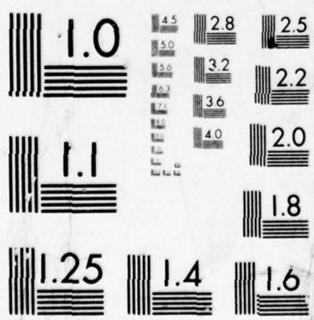

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SLIDE 2

There is no doubt that the inclusion of RIW, FFW, LCC or DTC in a contract will represent added expenditures. Some RFP's are being prepared by outside consultants to the Government, at considerable cost. Responding to these RFP's certainly adds a burden to the contractor. These costs may be compensated for by reduced data requirements or reduced testing requirements but we have not seen any such advantage as yet. On the contrary, documentation requirements have often increased. The cost to both the military and the Contractor to administer and manage these contracts all represent added expense. If the long term savings do occur, then these added expenses might be justified. However, it is necessary to look at all of the costs that will be incurred in the preparation and implementation of the contract.

NEW DESIGNS

ON NEW DESIGNS, IT IS DIFFICULT, IF NOT IMPOSSIBLE, TO ESTIMATE WITH ANY DEGREE OF ACCURACY THE COST OF MEETING THE WARRANTY OBLIGATION OR THE LCC VERIFICATION.

THE CONTRACTOR MUST ESTIMATE:

RELIABILITY (Quantity of spares, Frequency of repairs)

MAINTAINABILITY (Repair times, Material costs)

NORTHROP
Electronics D[illegible]on

SLIDE 3

The biggest problem area, and the most common contractor comment is that it is usually difficult and often impossible to accurately predict reliability and maintainability parameters on new equipment. Some pioneering effort is underway in this area, but it will be some time before the techniques are developed and even longer before they are tested and accepted. Field demonstrated reliability and maintainability often depends on how and where the equipment is used, operated and maintained. The contractor is often put in a position of risking his profit and more to meet these requirements. Of course he has the option of "no bidding" and some do. But if your business is and has always been with the military, and if you want to play, it's the only game in town.

THE ATTITUDE OF THE GOVERNMENT IS
THAT IMPROVED RELIABILITY IS SOLELY
WITHIN THE CONTRACTOR'S CONTROL.

HOWEVER - - - -

RELIABILITY IS A FUNCTION OF:

1. Operating time
2. Use environment
3. Experience and capability of operating and maintenance personnel
4. Training

NORTHROP
Electronics Division

SLIDE 4

An additional area that I feel is misunderstood is the often quoted statement that Warranties and LCC contract requirements make the contractor responsible for the Operating and Maintenance phase of the program. Prior to these new contracting concepts, when the hardware was delivered, the contractor's obligation was terminated. But now, the contractor will continue to be responsible until his warranty or LCC verification period has terminated. This is certainly true, but the contractor really doesn't have sole responsibility as some would lead you to believe. The military operates and maintains the equipment and the factors surrounding that activity are of great importance in determining the actual reliability and maintainability of the hardware. These factors are usually not under the control of the contractor. Unless the contractor has control, or firm guidelines describing his liability are negotiated, then contractor risks can be unacceptably large.

PROBLEM AREAS

* INDUSTRY / MILITARY COMMUNICATION
* CONTRACTOR RISK
* REDUCTION OR INCREASE IN COMPETITION

NORTHROP
Electronics Div.

SLIDE 5

There are a number of other problem areas that can be identified and discussed regarding these new contracting criteria. I have identified three that I feel merit mentioning.

For both the military and industry to be successful, the level of communication must increase. We have existed in an environment where we often find it expedient not to reveal certain information to each other for one reason or another. It may be very difficult to break down this barrier that has developed over the years in customer/contractor relationships, but there must be complete honesty and openness for success. Surprises can be disasterous.

It seems that everyone who is promoting Warranties, DTC and LCC contracts would have you believe that if the contract is successful everyone wins, and if either the Government or the contractor should lose, both will lose. I don't believe it. I have reviewed many RFP's and responded to some where the contractor risk is obvious - non-performance will cause a downward adjustment in contract price. The Government has no risk since there is no reward for good performance. Unfortunately, many RFP's do not necessarily follow the DOD guidelines resulting in sizeable contract risks without the opportunity for reward.

There are considerable differences of opinion within the Electronic community as to whether these new contracting schemes reduce or increase competition. In one case, a military service released a RFP to 27 contractors and they received only 2 bids. I have heard some that consider warranties, DTC and LCC as marketing gimmicks, some feel they are good, some think they are too risky, while others accept the new concepts because they are contracting requirements.

It appears that these programs would be more profitable to the military as well as the contractor if more consideration were given to reducing contractor risk.

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LIFE CYCLE ANALYSIS
- A SHORT REFLECTIVE APPRAISAL -
(FOR WEAPON SYSTEMS IN THE DSARC/CAIG PROCESS)

- OBJECTIVE
- APPLICATIONS
- OBSERVATIONS
- MAJOR CONSTRAINTS
- IMPROVEMENTS

MARCO FIORELLO
LMI

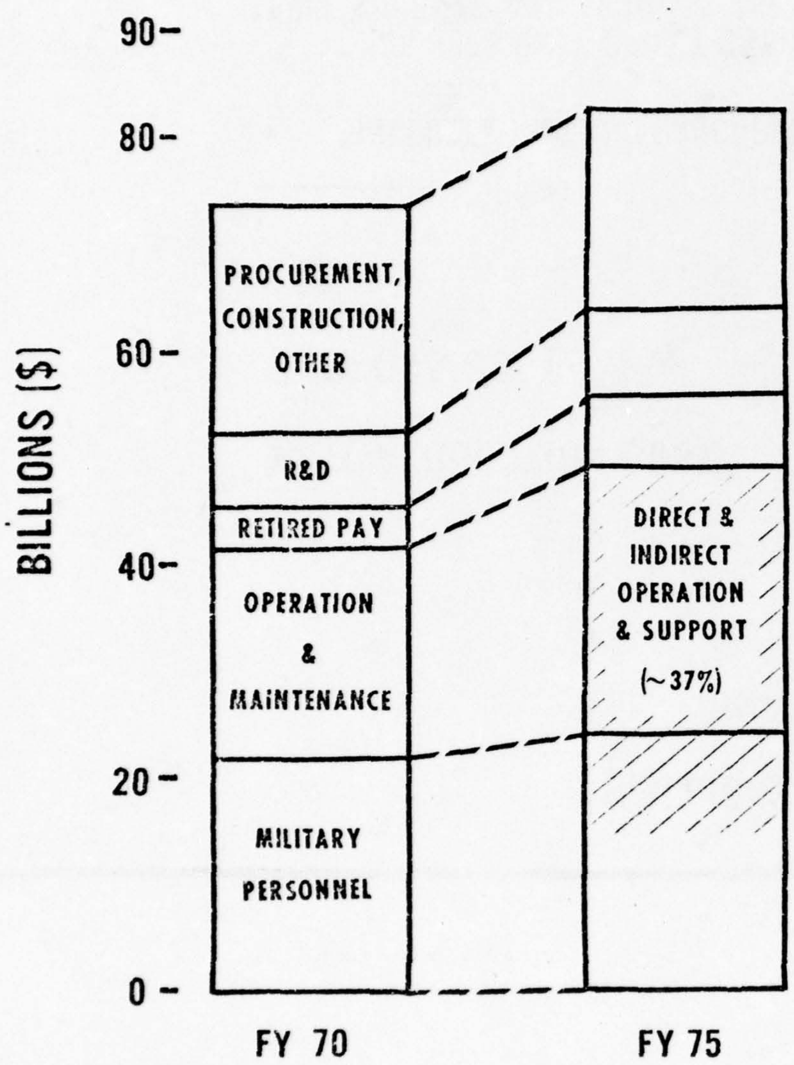
OBJECTIVE: TO ACHIEVE A REQUIRED CAPABILITY AT A MINIMAL LCC (R&D + PROD + O&S)

APPLICATIONS:

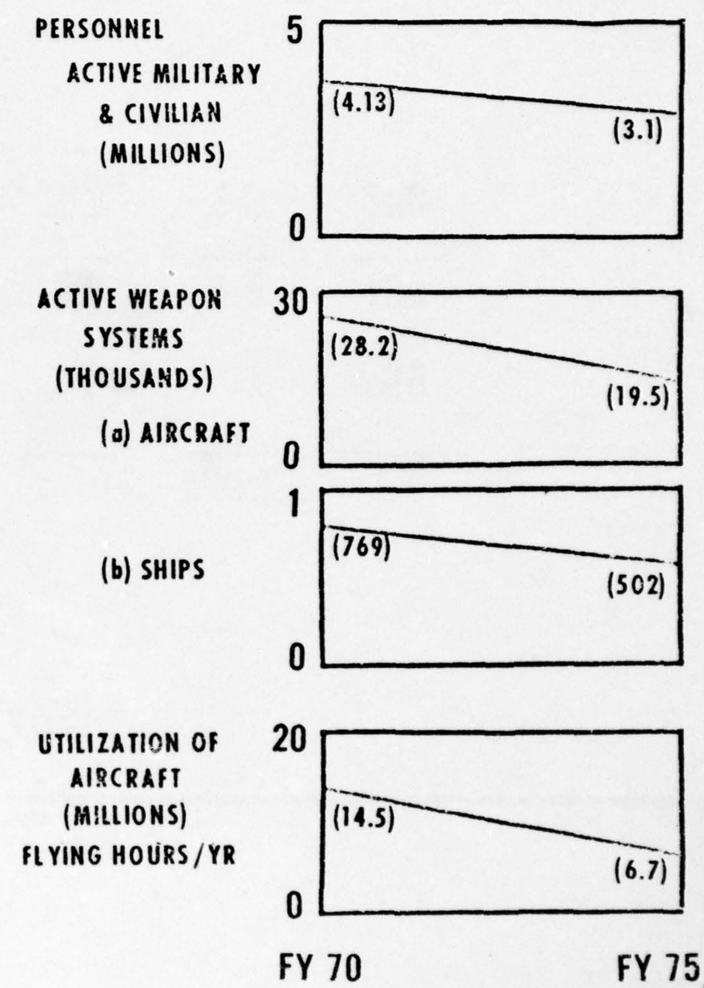
- FORCE STRUCTURE/BUDGET IMPACT ANALYSIS
- WEAPON SYSTEM COMPARISONS
- TRADE-OFF ANALYSIS FOR DESIGN IMPROVEMENT
- DEVELOPMENT MONITORING
- TREND ANALYSIS

DEFENSE OUTLAYS

(CURRENT YEAR DOLLARS)



SIGNIFICANT TRENDS



SIGNIFICANCE OF O&S COSTS

(MILLIONS OF DOLLARS)

(UNADJUSTED)

	A-7D	A-10	XM-1	PF
UNIT-ACQUISITION COST[1]	4.2	3.5	.7	50
UNIT-O&S COSTS[2]	8.7	7.8	2.2	150
LCC	12.9	11.3	2.9	200

[1] INCLUDES R&D AND PROCUREMENT

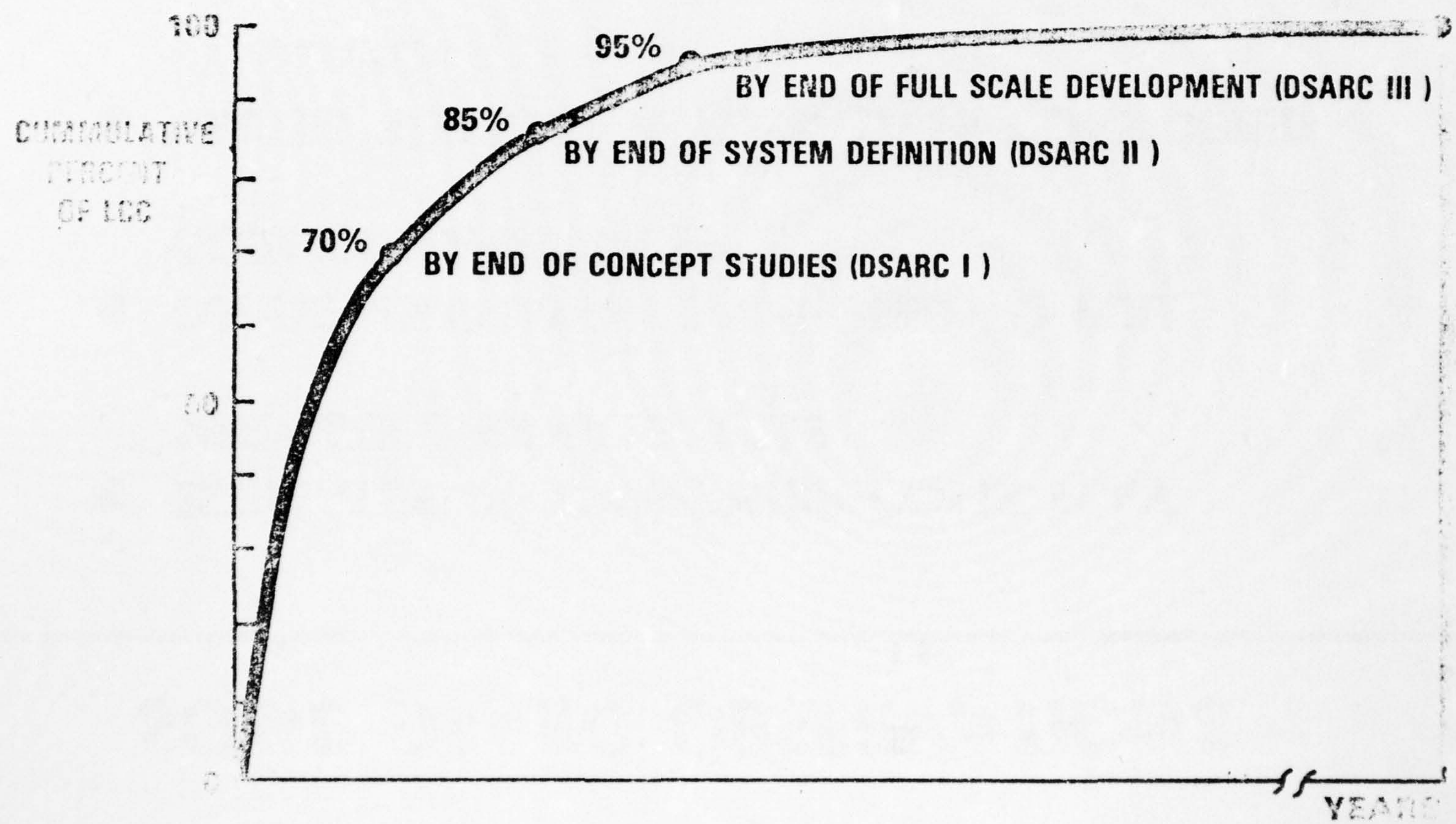
[2] INCLUDES ONLY DIRECT O&S COSTS AND OTHER BATTALION OR SQUADRON LEVEL SUPPORT; AND ASSUMES THE FOLLOWING OPERATIONAL LIFE:

TANK	(XM-1)	-- 10 YEARS
AIRCRAFT	(A-7D, A-10)	-- 15 YEARS
SHIP	(P-F)	-- 30 YEARS

LIFE CYCLE COSTING IN SYSTEM ACQUISITION

REVIEW OF THE DSARC/DCP PROCESS

EARLY DECISIONS DETERMINE LCC



SOME DSARC OBSERVATIONS

- ESTIMATES OF OWNERSHIP COSTS PLAY VERY SUBORDINATE ROLE
- DSARC USUALLY NOT EXPOSED TO FULL COST CONSEQUENCES
- LIMITED SUPPORT ALTERNATIVES CONSIDERED BY DSARC
- LITTLE ANALYSIS OF O&S COST SENSITIVITY TO
  - Reliability and maintainability changes
  - Alternative support policies

PRINCIPAL CONSTRAINTS

DATA

- MULTIPLE DATA PRODUCTS REQUIRED
- MULTIPLE NOMENCLATURE
- POOR QUALITY
- APPROXIMATE VALUES
- LIMITED HISTORICAL DATA BASE
- INTERSERVICE INCONSISTENCIES

IMMATURE METHODOLOGY

- PARTIAL LCC PERSPECTIVE
- LIMITED POLICY AND SYSTEM LEVEL ADJUSTMENTS
- LIMITED COMPONENT - SYSTEM COMPATIBILITY
- INCOMPLETE MARGINAL O&S COST IMPACT ANALYSIS
- MODEL PROLIFERATIONS
- LOGICAL LOOPHOLES
- INTERSERVICE INCOMPATIBILITIES

INSTITUTIONAL DISINCENTIVES

$$\left.\begin{array}{l}\bullet\ \text{SERVICES}\\ \bullet\ \text{CONTRACTORS}\\ \bullet\ \text{DoD}\end{array}\right\}\ \text{NOT YET FULL - TOP-LEVEL MANAGEMENT COMMITMENT}$$

WHAT'S BEING DONE

- INCREASED CONSIDERATIONS OF LCC IN SYSTEM PROCUREMENT
  - O&S COST THRESHOLDS: F-16/F-18
- VISIBILITY AND MANAGEMENT OF SUPPORT COST
  - SERVICE & DoD TASKS
  - SYSTEM: ITEM VISIBILITY
- CAIG O&S COST DEVELOPMENT GUIDES
  - ALL WEAPONS COVERED
  - SERVICE COMPARABLE O&S COST ELEMENT STRUCTURES
  - O&S COSTS AND R&M LINKAGE
  - COSTING GUIDANCE

WHAT NEEDS TO BE DONE

- INCORPORATE POLICY IMPACTS
  - MANNING
  - SUPPORT
- CLOSE THE LOOP BETWEEN FORCE STRUCTURE ISSUES AND INDIVIDUAL SYSTEM LCC
- FEWER MODELS - MORE PRINCIPLES
- WHITHER LCC MANAGEMENT OF SYSTEMS
  - IS IT POSSIBLE?
  - DO WE WANT IT?
  - WILL IT BE EFFECTIVE?

HAROLD BALABAN
ARINC

SOME RECENT MILITARY RIW PROCUREMENTS

- Air Force
  - ARN-118 TACAN Set
  - Units on F-16 Aircraft
  - INS — C-141 Aircraft
- Army
  - ARN-123 VOR/ILS Radio Set
  - LDNS Doppler Navigation Set
- Navy
  - APN-194 Radio Altimeter
  - Hydraulic Pump — F-14 Aircraft

RELIABILITY IMPROVEMENT WARRANTY CONCEPT

Contractor performs depot-type repair services at a pre-established total price for a specified number of years.

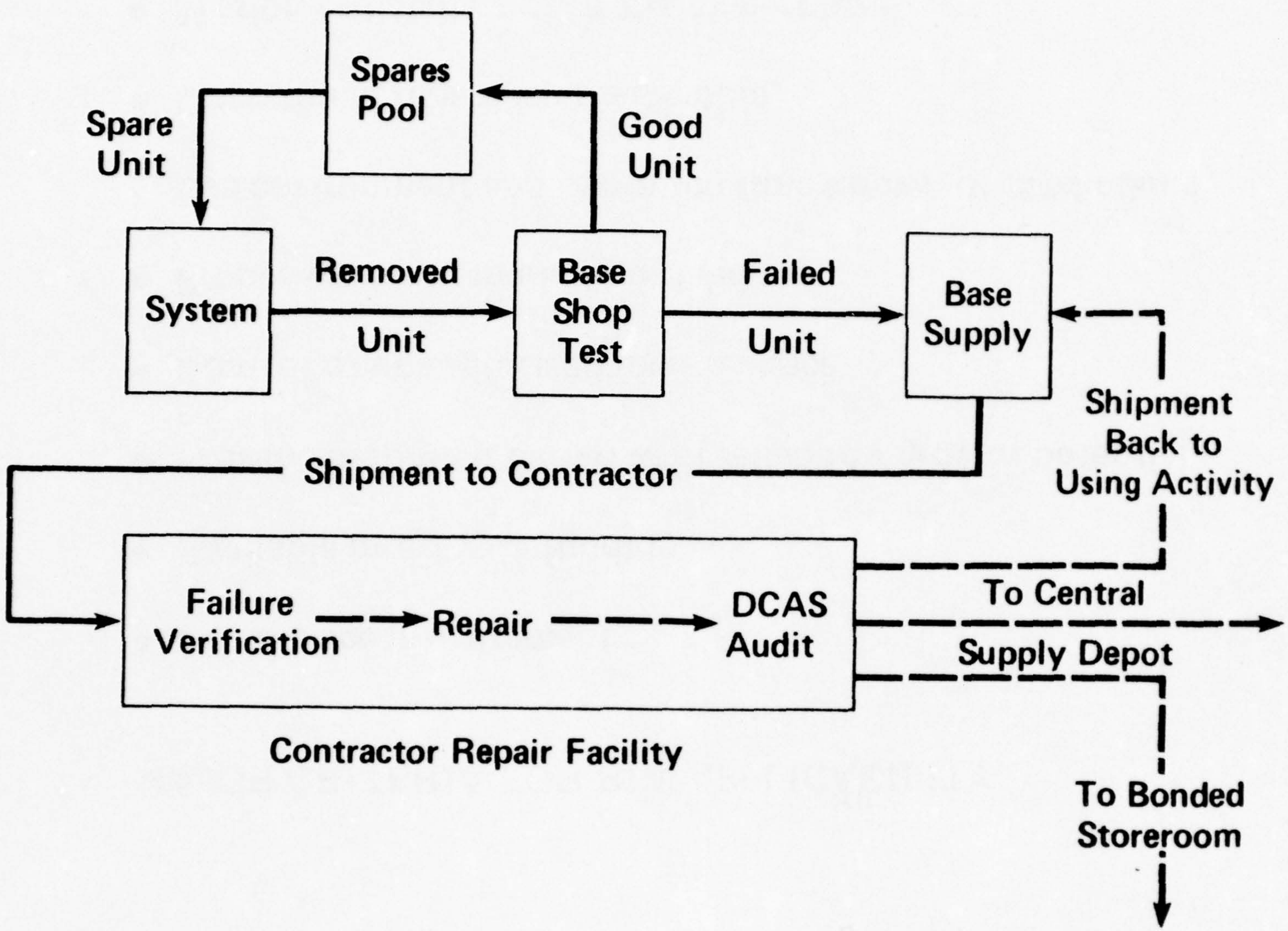
WARRANTY POTENTIAL

Extend producer's responsibilities to include operational R&M performance thereby providing motivation to design, produce, and maintain acceptable R&M characteristics.

SPECIFIC BENEFITS OF WARRANTY

- Reliability/maintainability incentive
- Real motivation for no-cost ECPs
- Minimal initial support investment
- Life-cycle cost control
- Reduced requirements for skilled military maintenance personnel
- Stabilized work flow and parts demand for contractor

TYPICAL WARRANTY-REPAIR FLOW



MAJOR CRITERIA FOR RIW APPLICABILITY

- Fixed-price procurement
- Available multi-year funding
- Proven equipment design with reliability growth potential
- Control of unauthorized maintenance
- Proper warranty marking or labeling
- Use environment and operating time known or predictable
- Operational reliability predictable
- Mission criticality not of the highest level

RIW TERMS AND CONDITIONS

- Warranty statement
- Contractor repair obligation
- Exclusions
- Warranty period
- Unverified failures
- ECP control
- Shipping
- Warranty pipeline flow

(continued)

RIW TERMS AND CONDITIONS (Continued)

- Contractor-turnaround-time requirement
- Government obligations
- Warranty data requirements
- Warranty labeling and seals
- Elapsed-time indicators
- Lost-unit adjustment
- Noncovered failures

GUARANTEED OPERATIONAL MTBF

- Contractor guarantees that operational MTBF will meet stated level.
- Failure to meet stated level results in:
  - Corrective action
  - Provision of loaner spares to improve operational readiness

POTENTIAL PROBLEM AREAS

- FUNDING - O&M VS. PROCUREMENT FUNDS
- ADMINISTRATION - NEW PROCEDURES AND DATA REQUIRED
- REDUCED SELF-SUFFICIENCY - CONTRACTOR DEPOT
- DISPUTES - MISTREATMENT, ENVIRONMENTAL EXTREMES

SOME RECENT MILITARY
RIW PROCUREMENTS

- Air Force
  - ARN-118 TACAN Set
  - Units on F-16 Aircraft
  - INS — C-141 Aircraft
- Army
  - ARN-123 VOR/ILS Radio Set
  - LDNS Doppler Navigation Set
- Navy
  - APN-194 Radio Altimeter
  - Hydraulic Pump — F-14 Aircraft

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NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

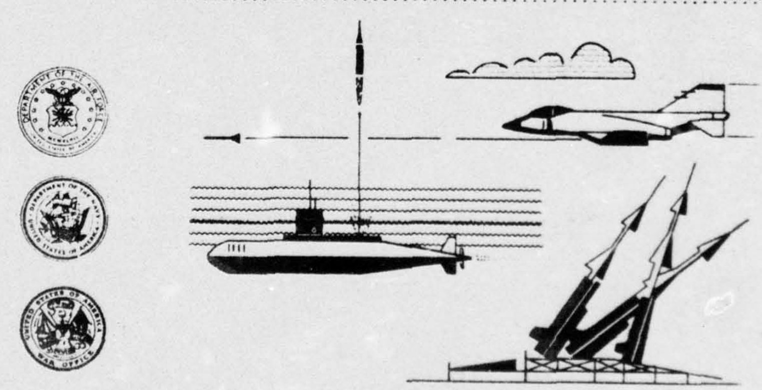
PLANNING GROUP

E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

STANDARDIZATION WORKSHOP

NOV. 18 – 19 1975

Joint Services Data Exchange Group for Inertial Systems



HOSTED BY

MACDILL AFB

and

HONEYWELL, AEROSPACE DIV.

ST. PETERSBURG FLA.

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RICK CLIMIE
AERONAUTICAL RADIO INC
CHAIRMAN

ROBER" ZIERNICKI, COL
HQ USAF

NO PHOTO AVAILABLE

JOHN MCHALE
HQ NAVAIR

ARINC INS STORY

- Comments presented at
- Joint Services Data Exchange Group
- For Inertial Systems
- Clearwater Beach, Florida - November 18, 1975

By

B. Richard Climie

Aeronautical Radio, Inc.

Aeronautical Radio, Inc.
2551 Riva Road
Annapolis, Maryland 21401

ARINC RESEARCH CORPORATION

AIRLINES
ELECTRONIC
ENGINEERING
COMMITTEE

AERONAUTICAL RADIO, INC.
2551 RIVA ROAD, ANNAPOLIS, MARYLAND 21401

W. T. [illegible] . . . . AEEC CHAIRMAN [illegible]
B. K. [illegible] . . . . AEEC VICE-[illegible]
D. H. [illegible]STONE . . . AEEC [illegible]
R. L. ADAMS . . . . . TRANS WORLD AIRLINES
A. R. A[illegible]LEGARTH . . . . GENERAL AVIATION
G. S. [illegible] . . . . . NORTHWEST AIRLINES
T. A. ELLISON . . . . . . UNITED AIRLINES
C. [illegible] . . . . [illegible]
H. F. HARRISON . . . . EASTERN AIR LINES
H. O. [illegible] . . . BRANIFF [illegible]
[illegible] W. [illegible] . . . . . . U.S. AIR FORCE
E. G. [illegible] . . . . DELTA AIR LINES
W. H. KING . . . . PAN AMER WORLD AIRWAYS
S. [illegible] . . . . . INTL AIR TRANSP ASSN.
H. R. [illegible]LYN . . . . . NATIONAL AIRLINES
J. [illegible] . . . . AIR [illegible]
J. [illegible] . . . . [illegible]
K. A. MOORE . . . . . CONTINENTAL AIRLINES
R. A. MOYERS . . . . U.S. AIR FORCE
M. [illegible] . . . . [illegible]
K. B. [illegible] . . . . . . AMERICAN AIRLINES
J. F. O'NEILL . . . . . ALLEGHENY AIRLINES
V. PER[illegible] . . . . [illegible]
J. R. [illegible] . . . . . . PIEDMONT AIRLINES
K. H. [illegible] . . . . [illegible]
W. S. [illegible] AVIONICS MAINT. CONF [illegible]
A. E. [illegible] . . . NORTH CENTRAL AIRLINES
L. [illegible] . . . . [illegible]
P. [illegible] . . . . WESTERN AIRLINES
S. B. [illegible](ADVISOR) . AIR TRANSP. ASSN.
F. C. WHITE(ADVISOR) . . . AIR TRANSP. ASSN.

AEEC Letter 75-789/INS-99
YEAR-SERIAL NO./PROJECT-ITEM NO.

To: AEEC Members

Date November 19, 1975

SUBJECT: THE ARINC INS STORY

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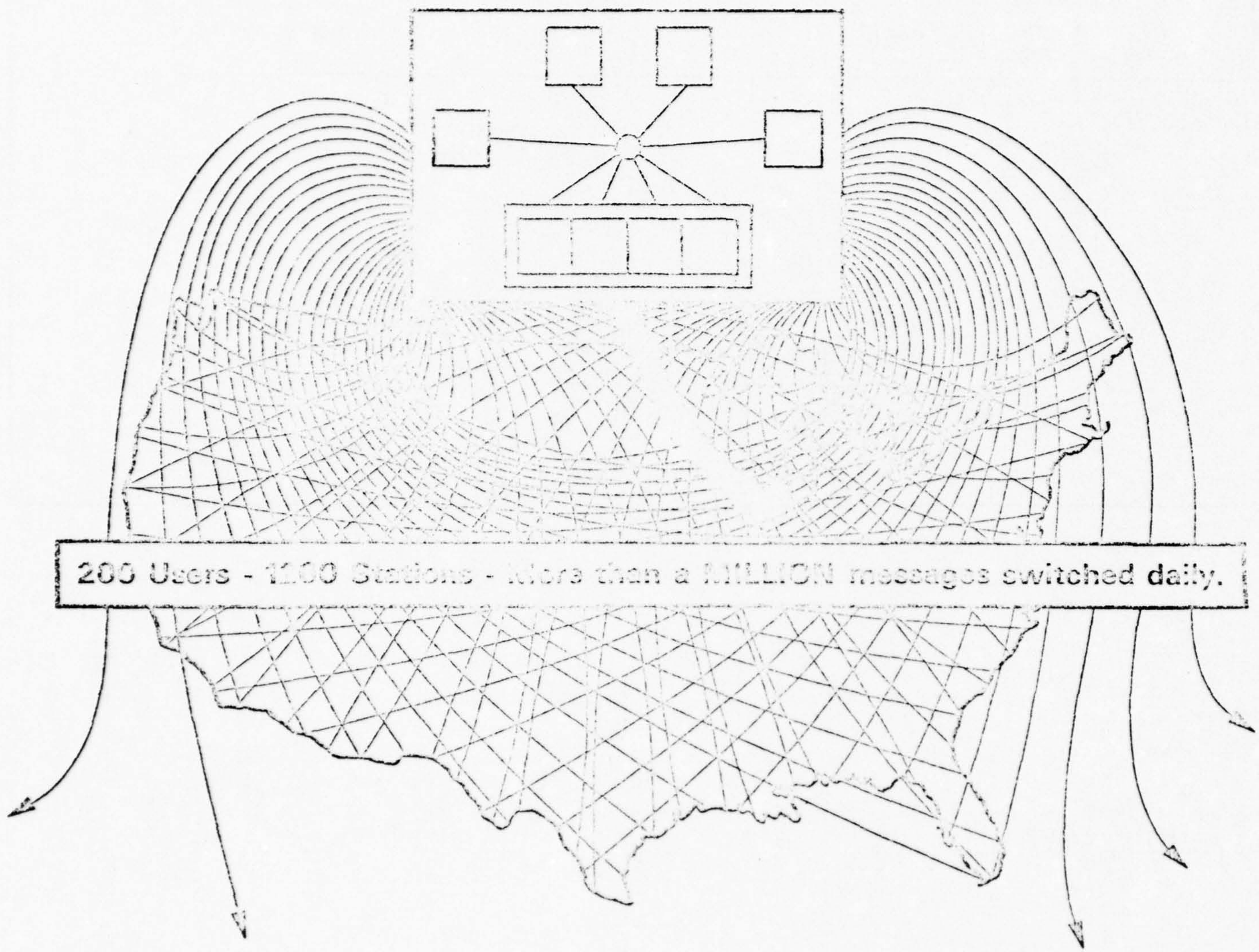
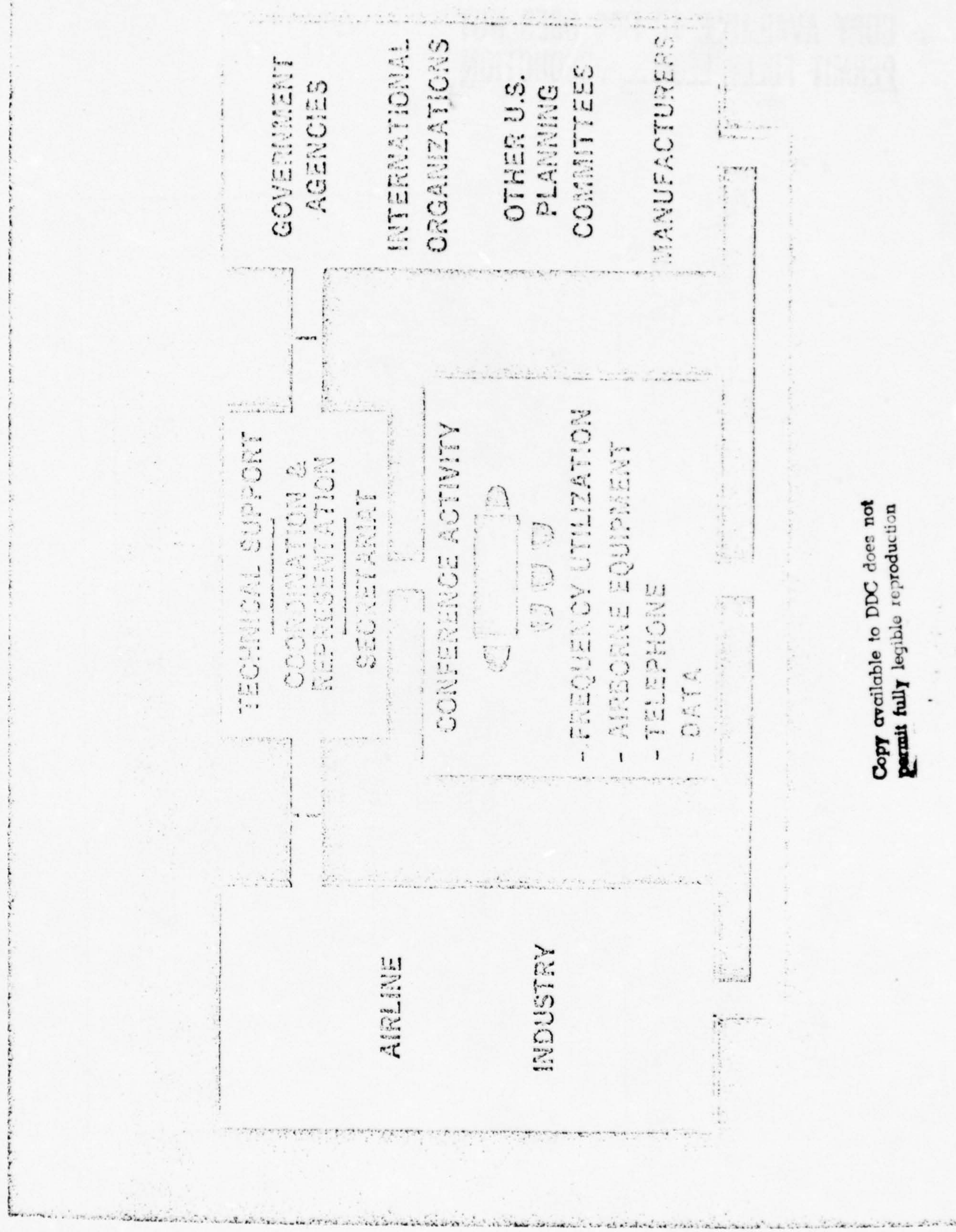
ARINC Electronic Switching System





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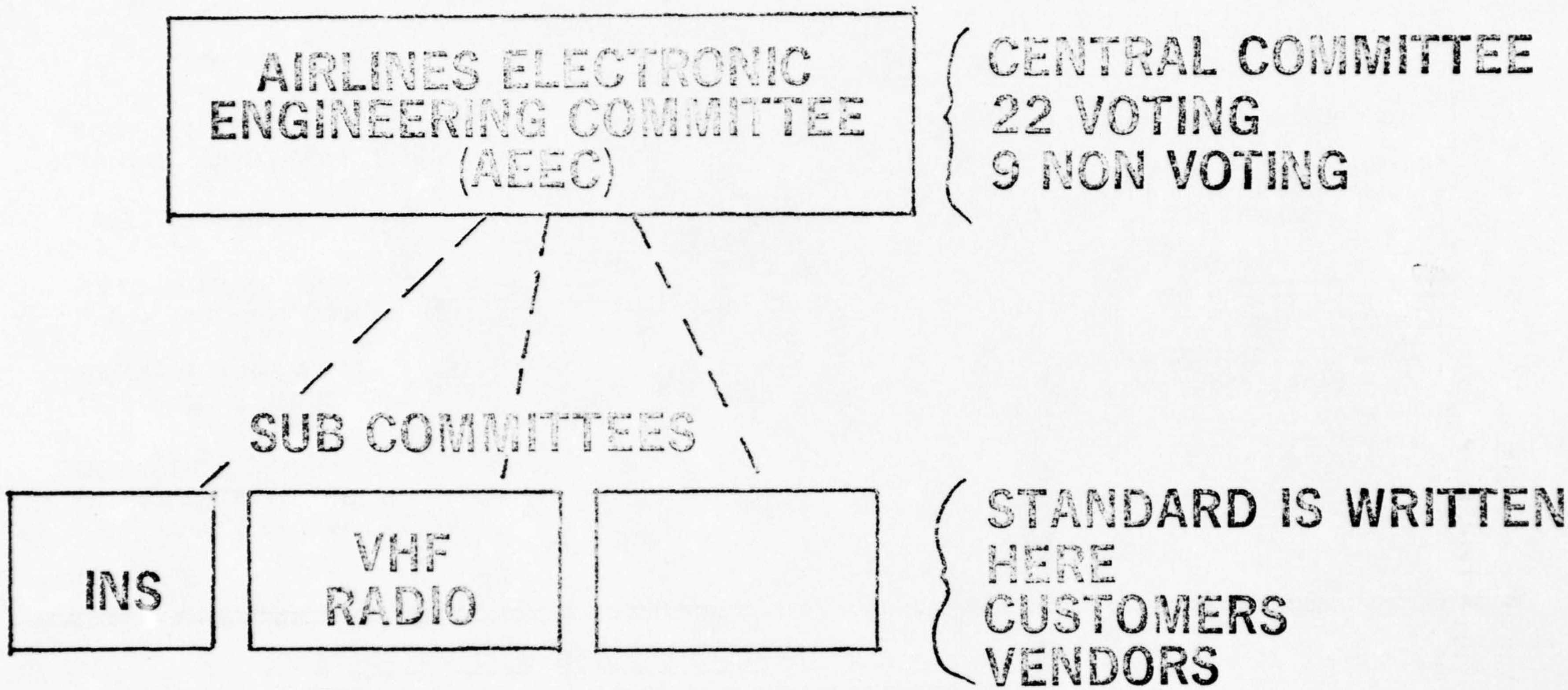
How AEEC Tackles Tough Topics

AIR TRANSPORT WORLD

AEEC: A Committee That Works

AIRLINES APPROACH



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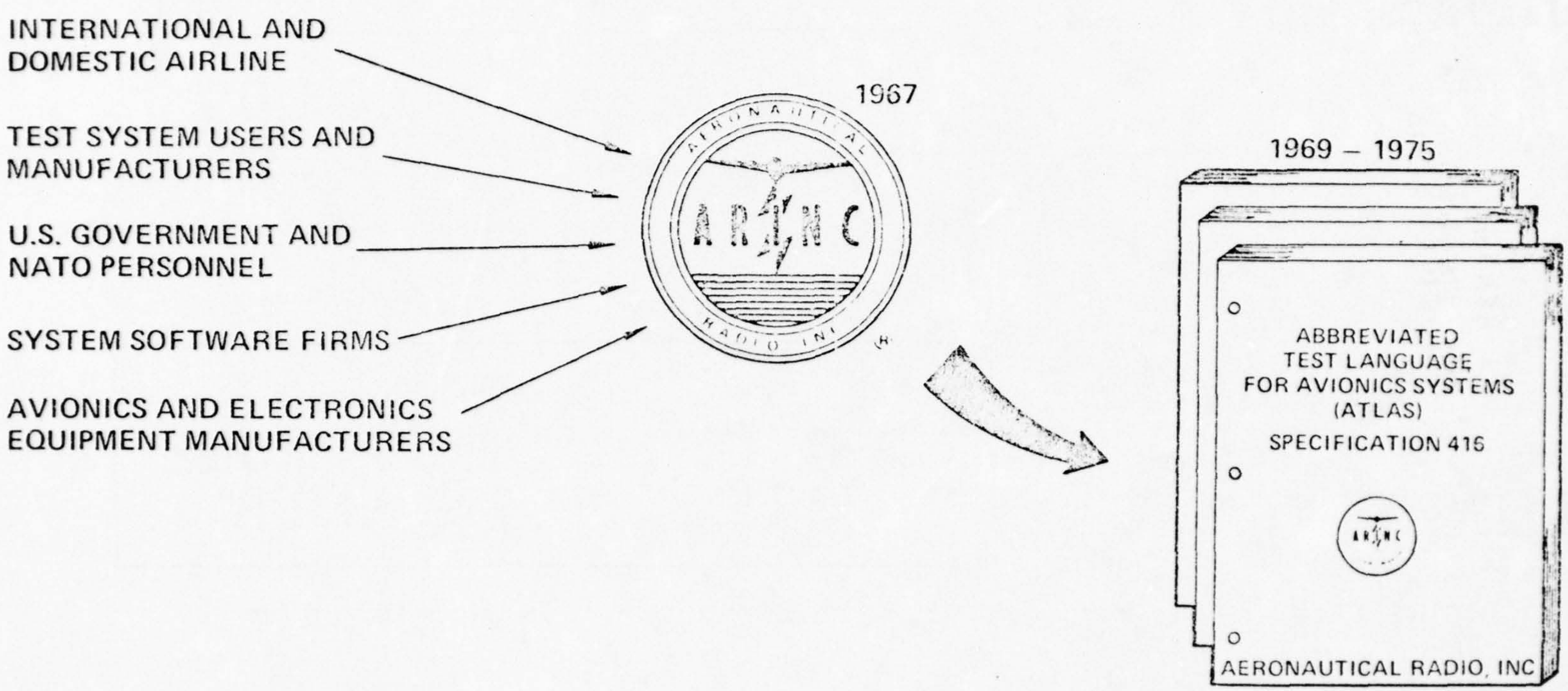
ATLAS SATISFIED A NATURAL INDUSTRY/CUSTOMER RECOGNIZED NEED FOR A STANDARD



RESULT OF THE ARINC-SPONSORED EFFORT HAS BEEN A SERIES OF ATLAS LANGUAGE SPECIFICATIONS AND MANY ATLAS SOFTWARE SYSTEMS

OPEN FORUM

- CONDITIONS FOR AN OPEN FORUM
  - FREE & OPEN EXCHANGE OF INPUTS
    - USERS
    - SUPPLIERS
      - INS
      - AIRFRAME
    - DEVELOPERS
  - ITERATIVE PROCESS
  - MUTUAL ACCEPTANCE

BEAR IN MIND .... "IT IS EASY TO ADOPT STANDARDS BUT
BUT NOT EASY TO GET THEM ACCEPTED."
CHAIRMAN, AEEC

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F^3 SPECIFICATION INTERFACES

- MECHANICAL
  - FORM FACTOR
  - SIZE
  - WEIGHT
  - MOUNTING
  - CONNECTORS
- ELECTRICAL
  - PIN ASSIGNMENTS
  - LOAD LEVELS
  - SIGNAL STRUCTURE
  - CABLES
- ENVIRONMENTAL
  - COOLING
  - DYNAMICS
  - PACKAGING EFFECTS
  - LOCATION
- SOFTWARE
  - LANGUAGE
  - DATA RATE

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AIR TRANSPORT INERTIAL NAVIGATION SYSTEM - INS

ARINC CHARACTERISTIC No. 561-11

561 ISSUED: JUNE 1, 1967
561-2 ISSUED: FEB. 1, 1968
561-6 ISSUED: JULY 15, 1970
561-7 ISSUED: AUGUST 31, 1971
561-8 ISSUED: JUNE 30, 1972
561-9 ISSUED: FEB. 1, 1973
561-11 ISSUED: JAN. 17, 1975

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AERONAUTICAL RADIO, INC.

INS 561 MILESTONES

- JANUARY 1965 - START
- MEETING REPORTS - BASICS
- JANUARY 1966 - FIRST DRAFT
- JANUARY 1966 - THREW OUT FIRST DRAFT
- FEBRUARY 1966 - SECOND DRAFT
- DECEMBER 1966 - AEEC APPROVED

LATER - SUPPLEMENTS

NOW - DASH 11

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BENEFITS OF A FORM, FIT & FUNCTION SPECIFICATION STANDARD INTERFACE

- INTERCHANGEABILITY
- MATURES EQUIPMENT DESIGN
- PROMOTES CONTINUING COMPETITION

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ROBERT ZIERNICKI, COL
HQ USAF

STANDARDIZATION-IS IT WORTH IT ?

NOT A PANACEA

- BENEFITS DO NOT ACCRUE AUTOMATICALLY
- WHEN APPROPRIATE & EFFECTIVELY IMPLEMENTED 15% TO 25% SAVINGS IN LCC OVER NONSTANDARD CAN BE EXPECTED

KEY TO STANDARDIZATION IS RECOGNIZING OPPORTUNITIES

INS IS AN OPPORTUNITY

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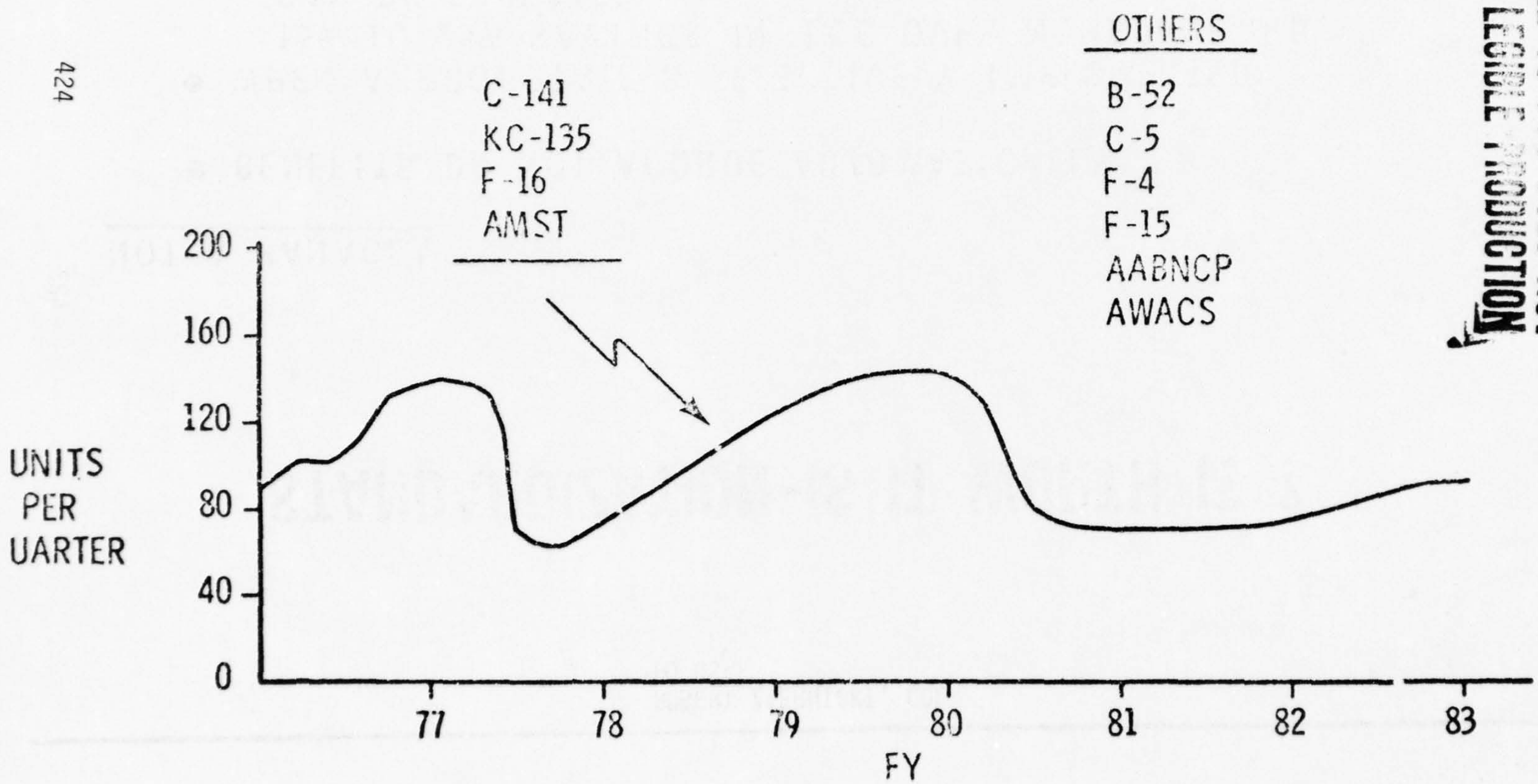
US AIR FORCE POTENTIAL NEW INS BUYS



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F^3 SPECIFICATIONS

- INTERFACES DEFINED FOR
  - MECHANICAL
  - ELECTRICAL
  - ENVIRONMENTAL
- SIGNAL FORMAT CHARACTERISTICS DEFINED

F^3 SPECIFICATION INTERFACES

- MECHANICAL
  - FORM FACTOR
  - SIZE
  - WEIGHT
  - MOUNTING
  - CONNECTORS
- ENVIRONMENTAL
  - COOLING
  - DYNAMICS
  - PACKAGING EFFECTS
  - LOCATION
- ELECTRICAL
  - PIN ASSIGNMENTS
  - LOAD LEVELS
  - SIGNAL STRUCTURE
  - CABLES
- SOFTWARE
  - LANGUAGE
  - DATA RATE

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BENEFITS OF A FORM FIT & FUNCTION SPECIFICATION (STANDARD INTERFACE)

- INTERCHANGEABILITY
- PROMOTES CONTINUING COMPETITION
- MATURES EQUIPMENT DESIGN
- REDUCE COSTLY GROUP "A" MODIFICATION COSTS
- REDUCE TRAINING/AGE NEEDS

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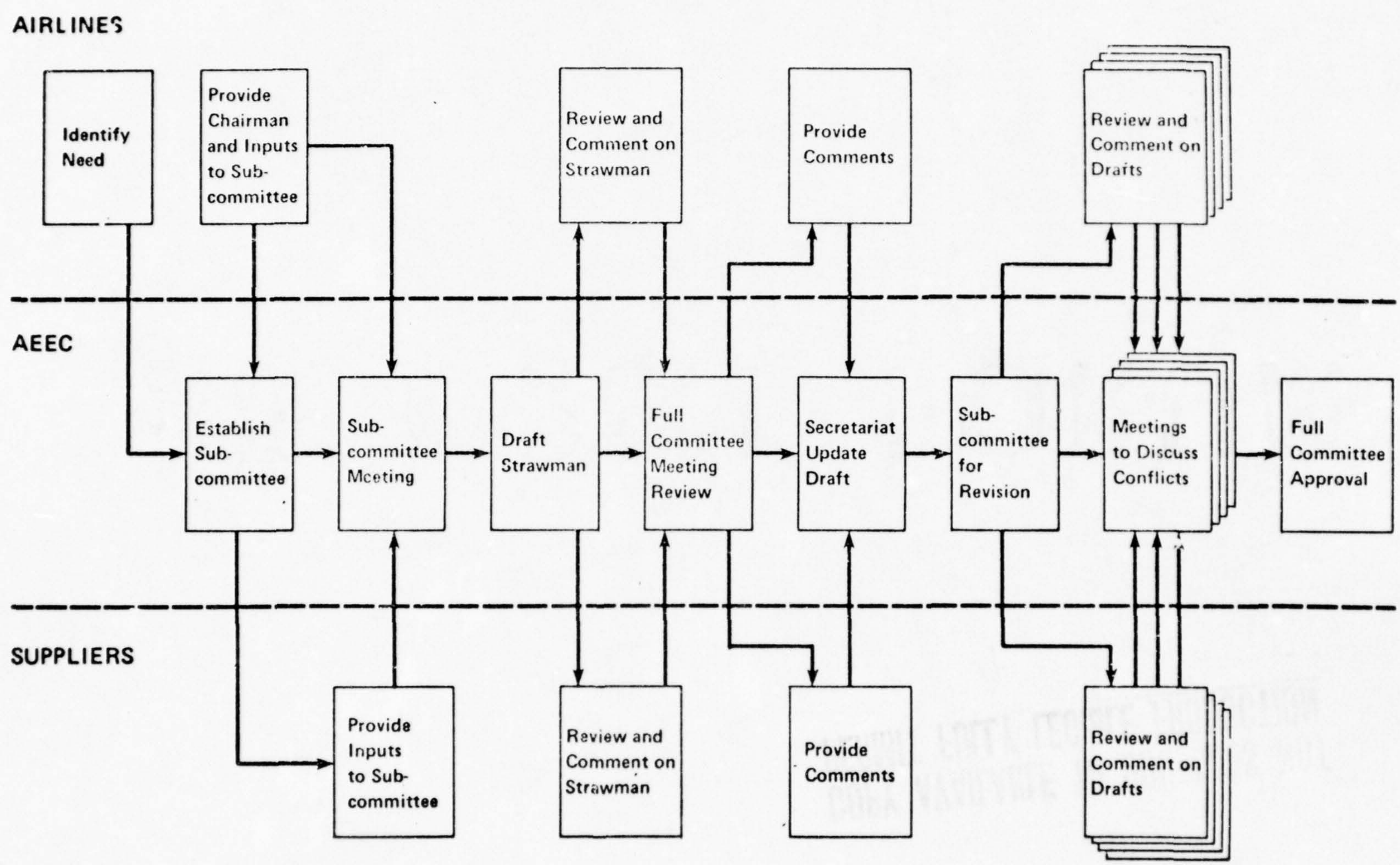
APPROACH

ADOPT THOSE COMMERCIAL PRACTICES THAT SUPPORT COST SAVINGS

- TECHNICAL
  - AF "STRAWMAN" SPEC - (FIRST DRAFT COMPLETED)
  - COMMENTS FROM PRIMES/VENDORS/DOD
  - ITERATE SPEC IN "OPEN FORUM" ENVIRONMENT
- BUSINESS
  - ESTABLISH SINGLE AGENCY FOR "FLIGHT ESSENTIAL" AVIONICS PROCUREMENT
  - ADOPT ACQUISITION & SUPPORT STRATEGIES THAT
    - STIMULATE & MAINTAIN COMPETITION
    - INCREASE VENDOR RESPONSIBILITY

EVOLUTION OF A CHARACTERISTIC



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AF OPEN FORUM

AF OPEN FORUM

PURPOSE

EVOLVE AND MAINTAIN A SPECIFICATION
FOR USE IN AIR FORCE INS
PROCUREMENTS

COPY AVAILABLE TO DDC DOES NOT PERMIT FULLY LEGIBLE PRODUCTION

COPY AVAILABLE TO DDC DOES NOT
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- CONDITIONS FOR AN OPEN FORUM
  - FREE & OPEN EXCHANGE OF INPUTS
    - USERS
    - SUPPLIERS
      - INS
      - AIRFRAME
    - DEVELOPERS
  - ITERATIVE PROCESS
  - MUTUAL <u>ACCEPTANCE</u>

BEAR IN MIND .... "IT IS EASY TO ADOPT STANDARDS BUT
NOT EASY TO GET THEM ACCEPTED."
CHAIRMAN, AEEC

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OPEN FORUM PARTICIPANTS

- SUPPLIER - INS MFR
- CUSTOMER - USING COMMAND/SPO
- LOGISTIC MANAGER - AFLC
- PROCUREMENT AGENCY - AFSC
- INTEGRATION/TEST AGENCY - CIGTF/PRIME CONTRACTORS
- OTHERS

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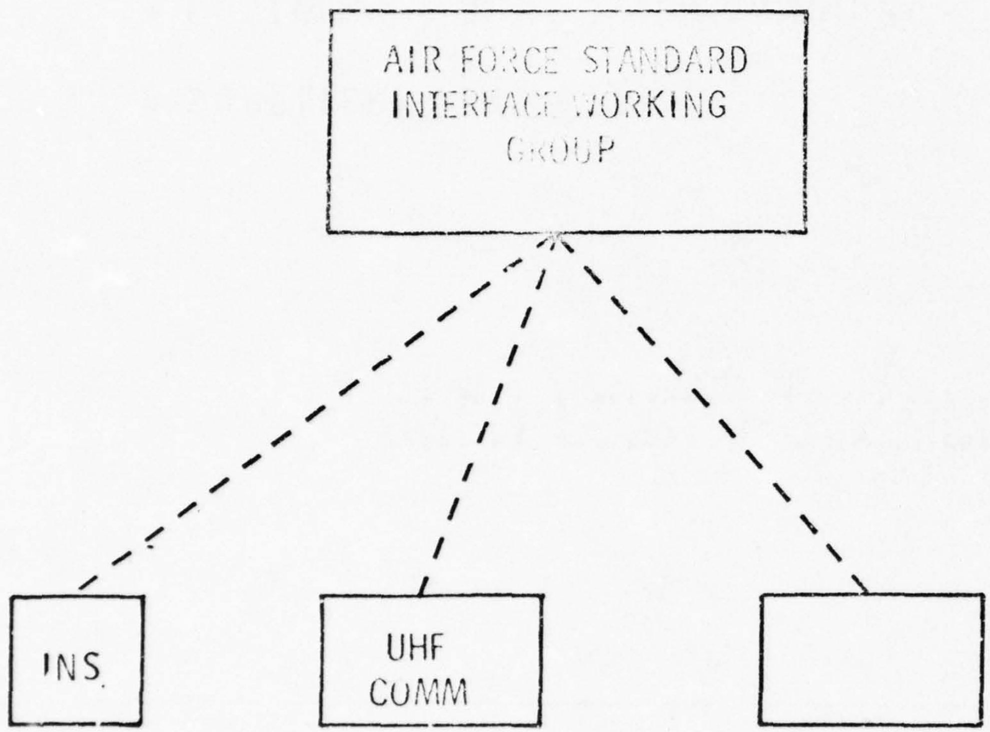
PROPOSED AF APPROACH



GROUP MEMBERS

1. CHAIRMAN ASD/RW
2. SAC
3. TAC
4. MAC
5. ASD/ENA
6. ACQUISITION AGENCY (ROTATING SLOT)
7. AFLC

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AIR FORCE STANDARD INTERFACE WORKING GROUP

- PURPOSE: TO GENERATE SPECIFICATIONS (F^3) FOR STANDARDIZED AVIONICS IN THE "OPEN FORUM" ENVIRONMENT
- SCOPE: ALL AVIONICS OPPORTUNITIES WHERE SUFFICIENT APPLICATIONS JUSTIFY A STANDARDIZATION EFFORT

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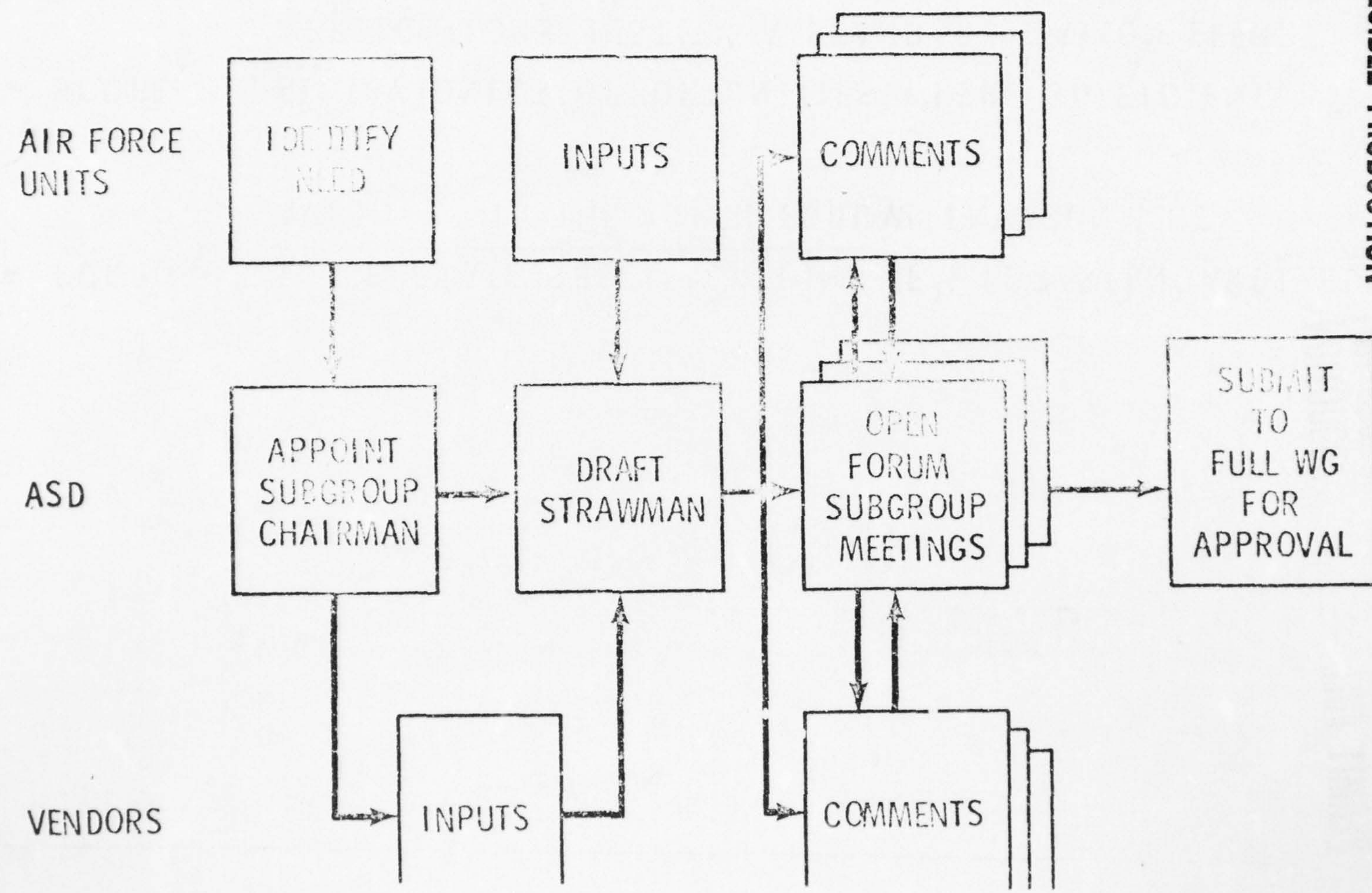
EVOLUTION OF AN AIR FORCE CHARACTERISTIC



AF [illegible] SCHEDULE (PARTIAL)

EVENT	AUG	SEP	OCT	NOV	DEC	JAN
SPEC OUT FOR COMMENT						
KICK OFF MTG		△ 23				
COMMENTS DUE BACK TO ASD			△ 24			
REISSUE PACKAGE OF COMMENTS TO DOD/INDUSTRY						
DOD/INDUSTRY REVIEW ALL PARTICIPANT'S COMMENTS						
PUBLIC MEETING NO. 1					2-3 DAYS	

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NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

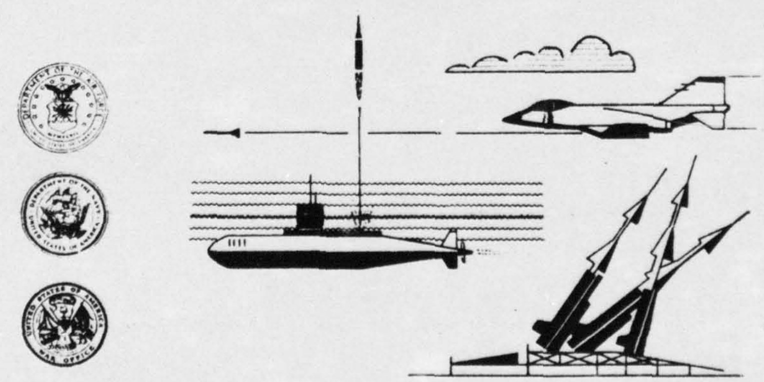
PLANNING GROUP

E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

BEARINGS WORKSHOP

NOV. 18 – 19 1975

Joint Services Data Exchange Group for Inertial Systems



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MACDILL AFB

and

HONEYWELL, AEROSPACE DIV.

ST. PETERSBURG FLA.

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BEARINGS WORKSHOP

WORKSHOP CHAIRMAN

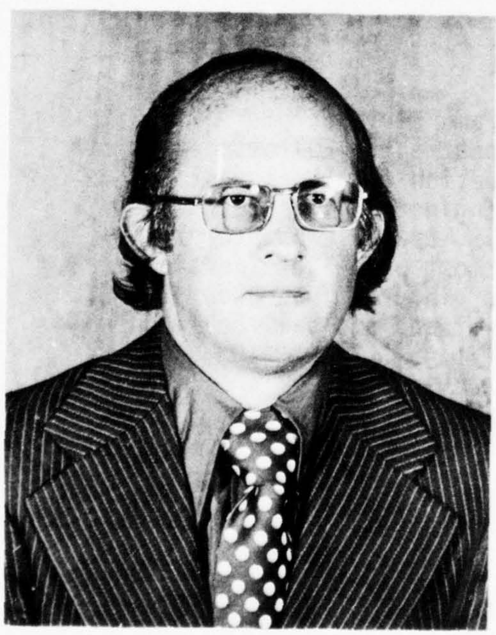
ALBERT P. FREEMAN

Albert P. Freeman leads the Air Force Programs Division of the C. S. Draper Laboratory Component Development Department. Following service in the U. S. Army in World War II and graduation from Northeastern University with a BS Degree in Mechanical Engineering, he joined the MIT Instrumentation Laboratory, now the C. S. Draper Laboratory. His activities at the Laboratory have involved most phases of inertial gyro and accelerometer technology. Of particular interest has been his CSDL bearing center work in the area of instrument gas and ball bearing fundamentals. He is a member of Tau Beta Pi, ASME, ADPA, ION, and is a registered professional engineer in Massachusetts.

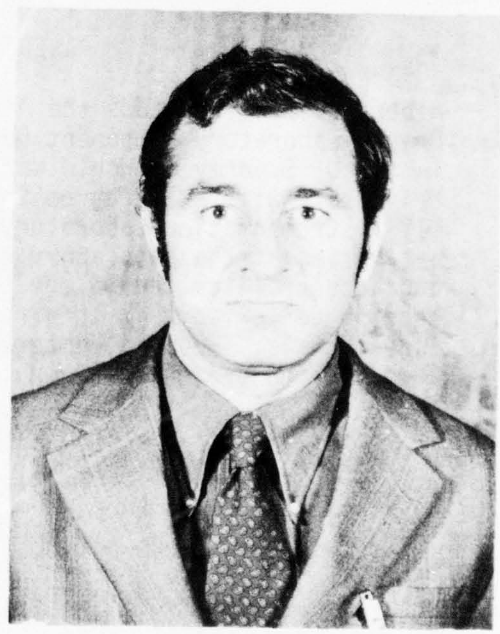
PANELISTS

ROBERT J. SCHIESSER
C.S. DRAPER LABORATORY

JOHN J. MURPHY
BARDEN CORPORATION



MALCOLM E. JONES
NASA, JOHNSON SPACE CENTER



LOUIS J. BLACHE
ROCKWELL INTERNATIONAL CORP

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

INSTRUMENT GAS AND BALL BEARING WORKSHOP

19 NOVEMBER 1975

CHAIRMAN

ALBERT P. FREEMAN

THE CHARLES STARK DRAPER LABORATORY, INC.

11/75 CD7678

INSTRUMENT GAS AND BALL BEARING WORKSHOP

RELIABILITY

PERFORMANCE

COST OF OWNERSHIP

READINESS

11/75 CD7679

INSTRUMENT GAS AND BALL BEARING WORKSHOP

AGENDA

MINI BRIEFING	BRIEFER
• Instrument Ball Bearing Diagnosis via Low Speed Torque Perturbation Analysis	John J. Murphy
• Dynamometer Method to Determine Residual Life and Reliability of Gas Spin Bearing Instruments	Louis J. Blache
• Use of a Precision Torque Measuring System to Evaluate Physical Condition of Gyro Spin Axis Bearings	Malcolm E. Jones
• Gas Bearing Reliability Assurance By Demagnetized Rundown Analysis	Robert J. Schiesser

PANEL DISCUSSION

- Instrument Bearing Reliability Discussion By Briefers and John K. Hanks

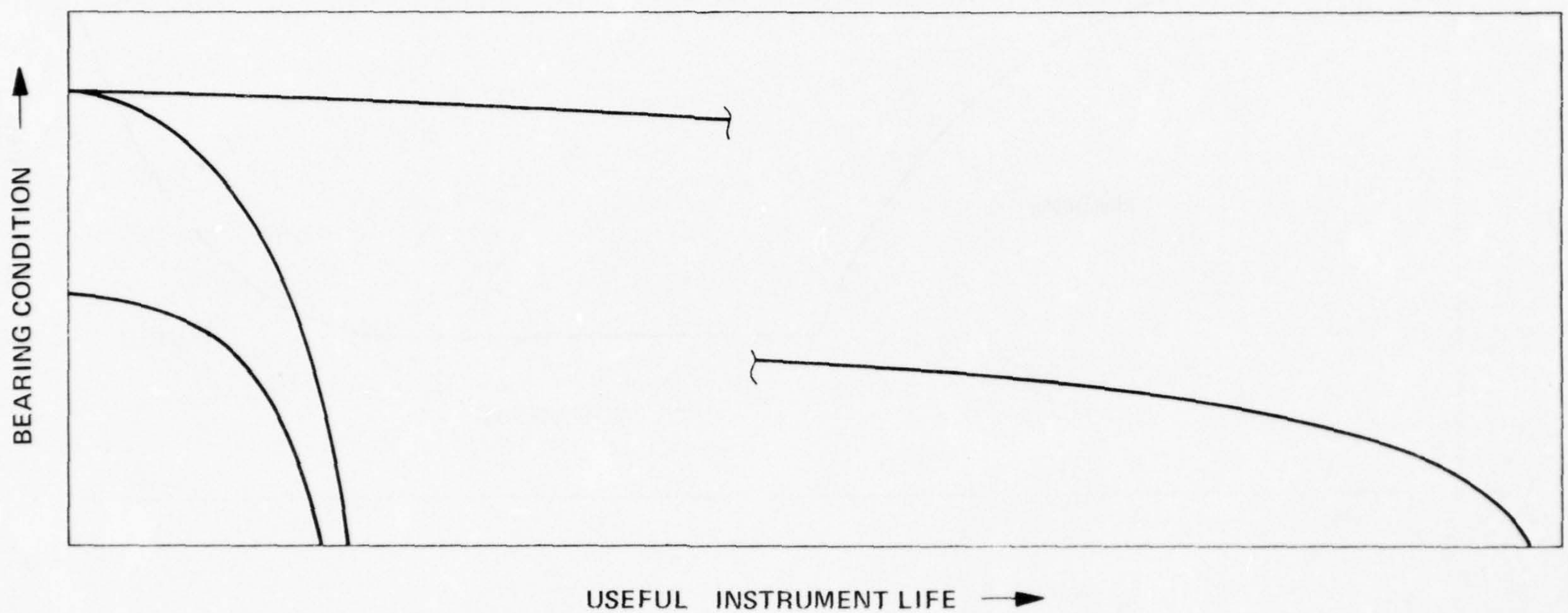
11/75 CD7680

INSTRUMENT GAS AND BALL BEARING WORKSHOP
RELIABILITY TESTING

- PREDICT RELIABILITY
  - INSTRUMENT, SYSTEM, MISSION
- EVALUATE MODIFICATIONS
  - QUALITY CONTROL, IMPROVEMENT PROGRAMS

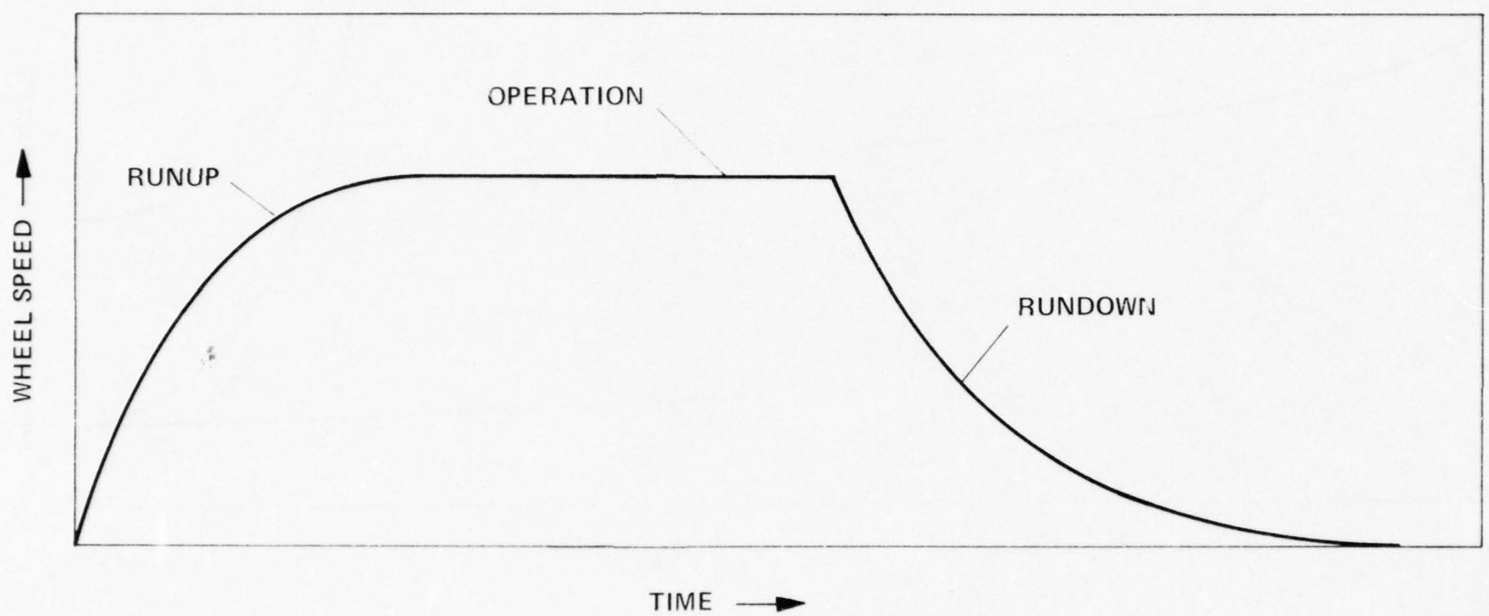
11/75 CD7681

INSTRUMENT GAS AND BALL BEARING WORKSHOP
INSTRUMENT RELIABILITY vs. BEARING CONDITION



11/75 CD7683

INSTRUMENT GAS AND BALL BEARING WORKSHOP
BEARING EVALUATION OPERATING MODES



11/75 CD7684

INSTRUMENT BALL BEARING DIAGNOSIS VIA LOW SPEED TORQUE PERTURBATION ANALYSIS

JOHN J. MURPHY
BARDEN CORPORATION
DANBURY, CONNECTICUT 06810

BEARING TORQUE

M = TOTAL BEARING TORQUE

$= M_t + M_r + M_c + M_l + M_s + M_h$

M_t → THRUST LOAD

M_r → RADIAL LOAD

M_c → CAGE

M_l → LUBRICANT

M_s → SEALS

M_h → HYSTERESIS

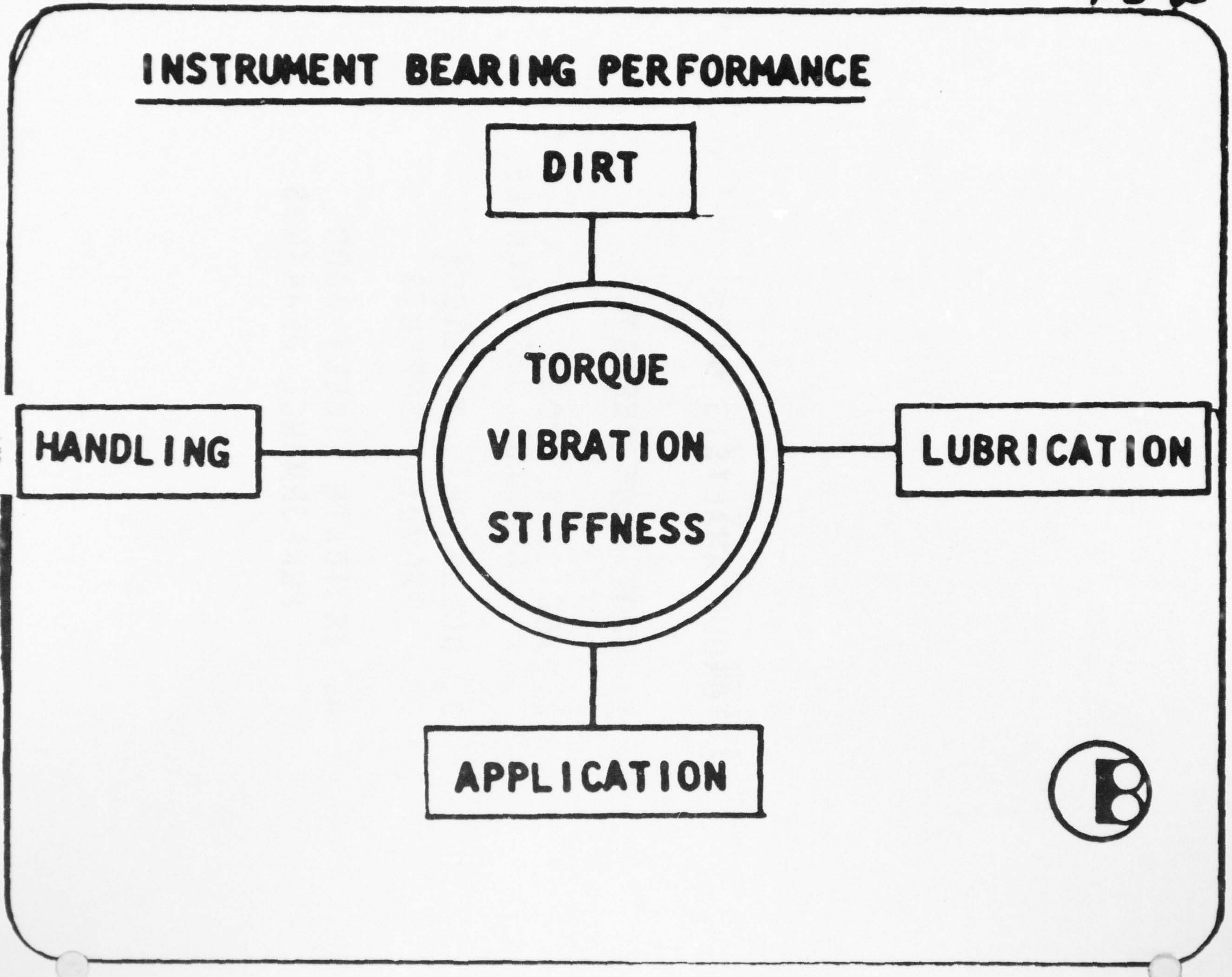
TORQUE ANALYSIS CAN:

1. SPOT RACE DEFECTS

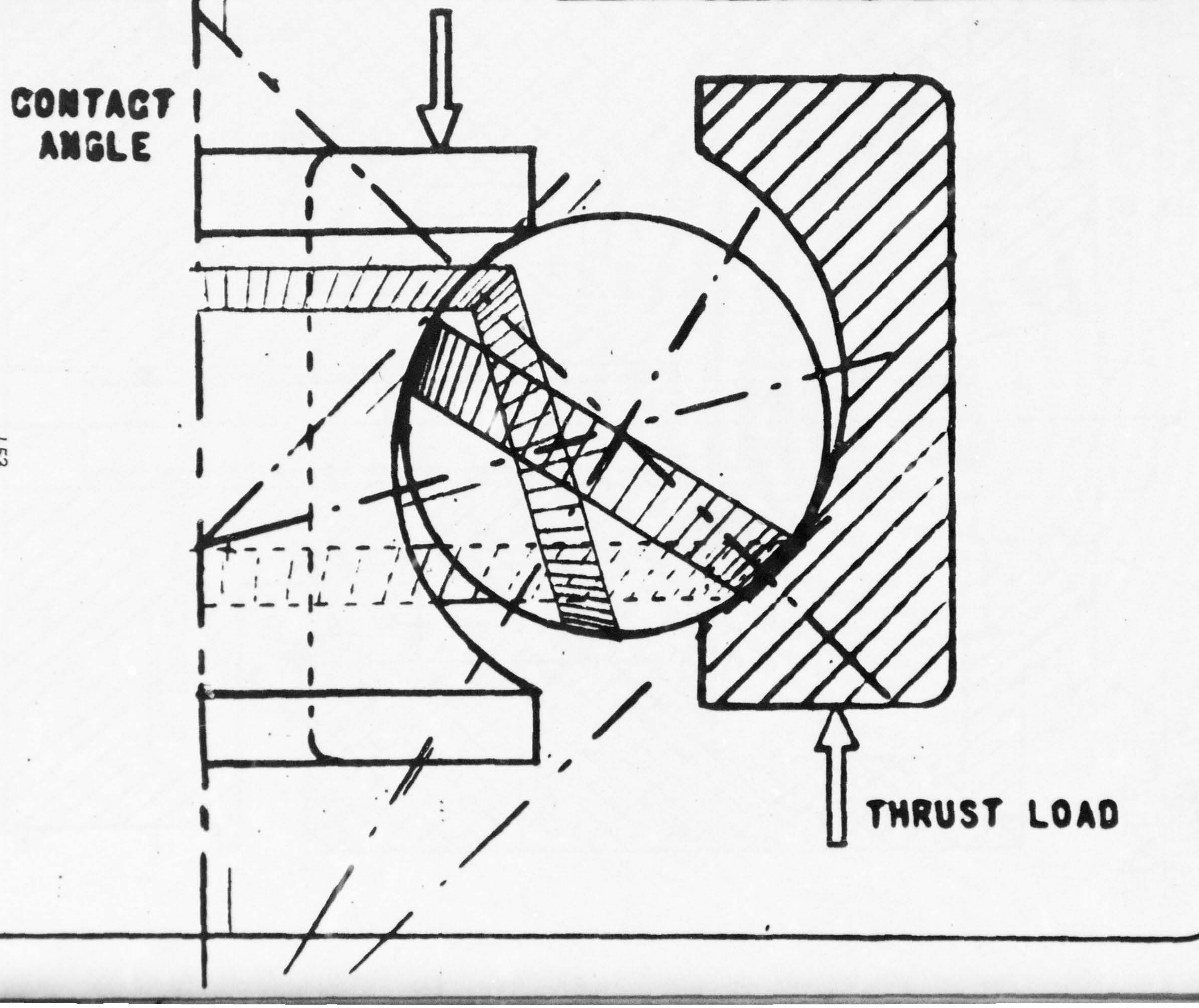
2. INDICATE GROSS
   SURFACE DIFFERENCES

3. OCCASIONALLY DETECT
   GEOMETRY EFFECTS

4. INDICATE LIKELY GOOD
   PERFORMANCE BEARINGS


INSTRUMENT BEARING PERFORMANCE
DIRT
TORQUE
VIBRATION
STIFFNESS
HANDLING
LUBRICATION
APPLICATION

BALL MOTION - THRUST LOAD



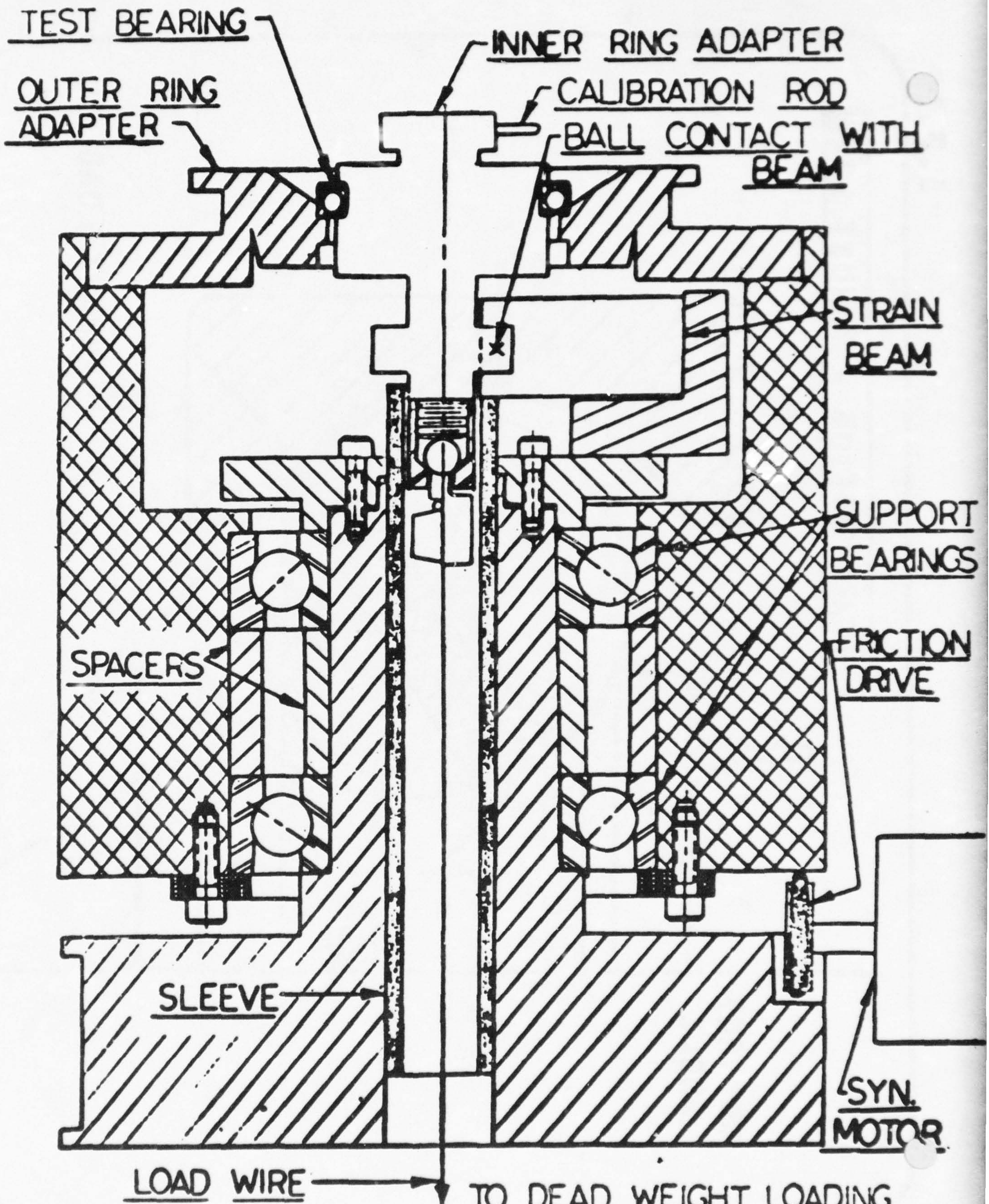
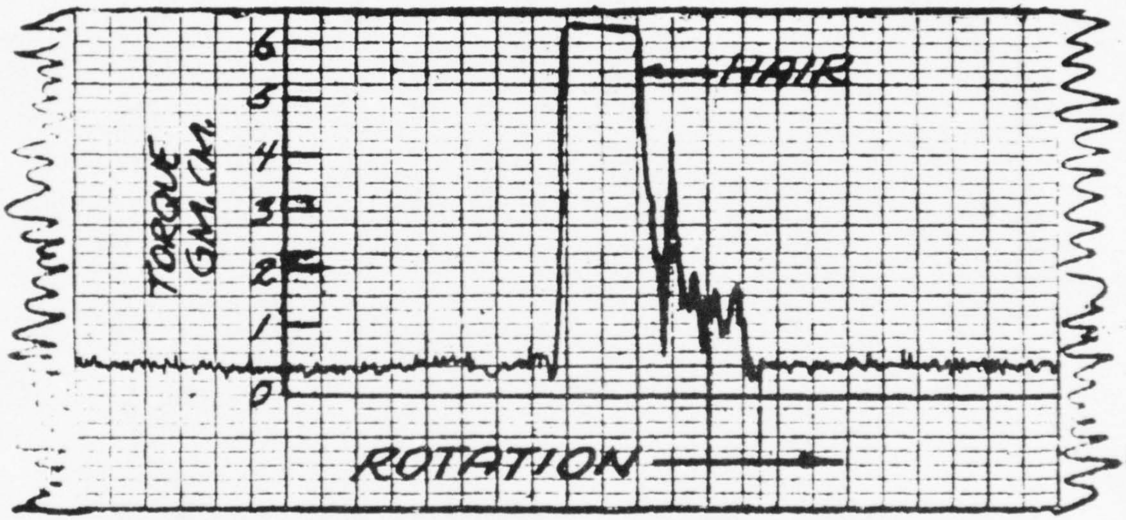


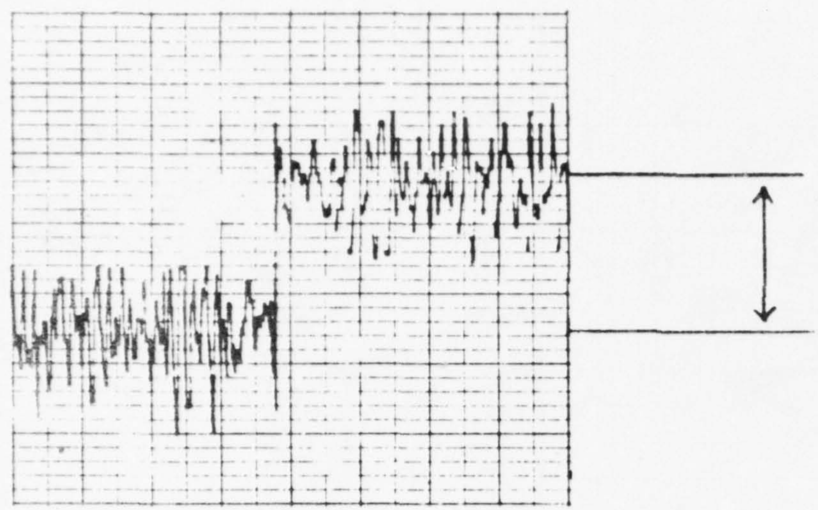
Figure 1. SCHEMATIC OF [illegible]

BEARING TORQUE



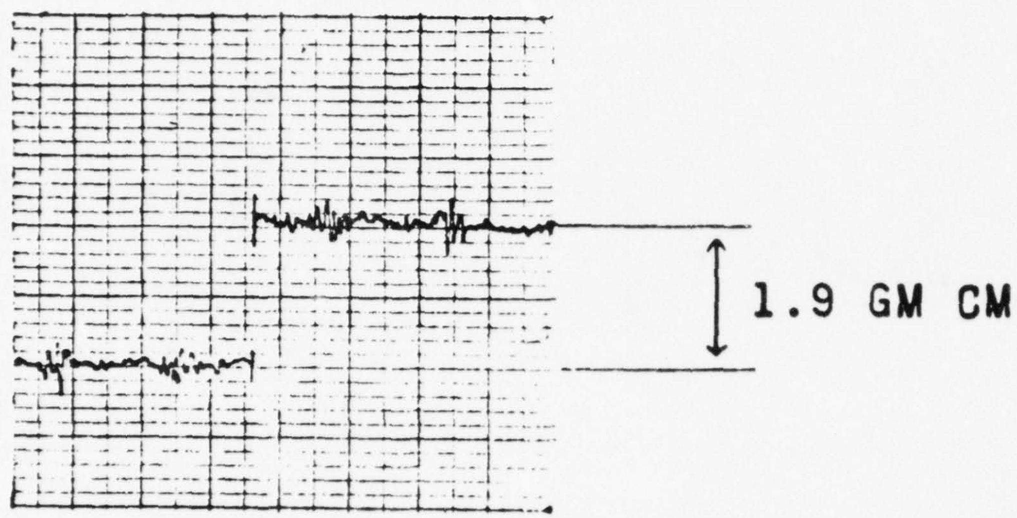
BEARING TORQUE
SR4 K 5
400 GRAM THRUST LOAD
TORKINTEGRATOR

SR4SS TORQUE PATTERN
GROUND RACES



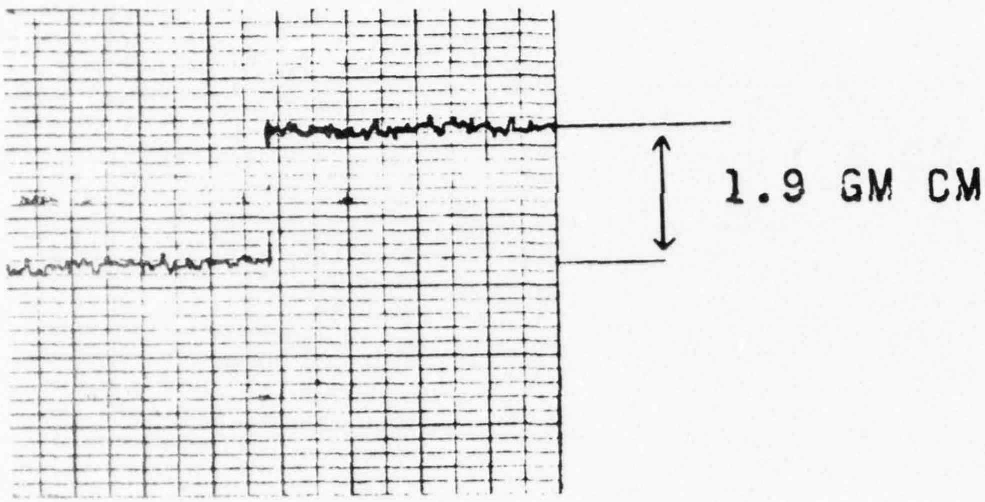
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
0-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
PAPER LAPPED INNER
PAPER LAPPED OUTER

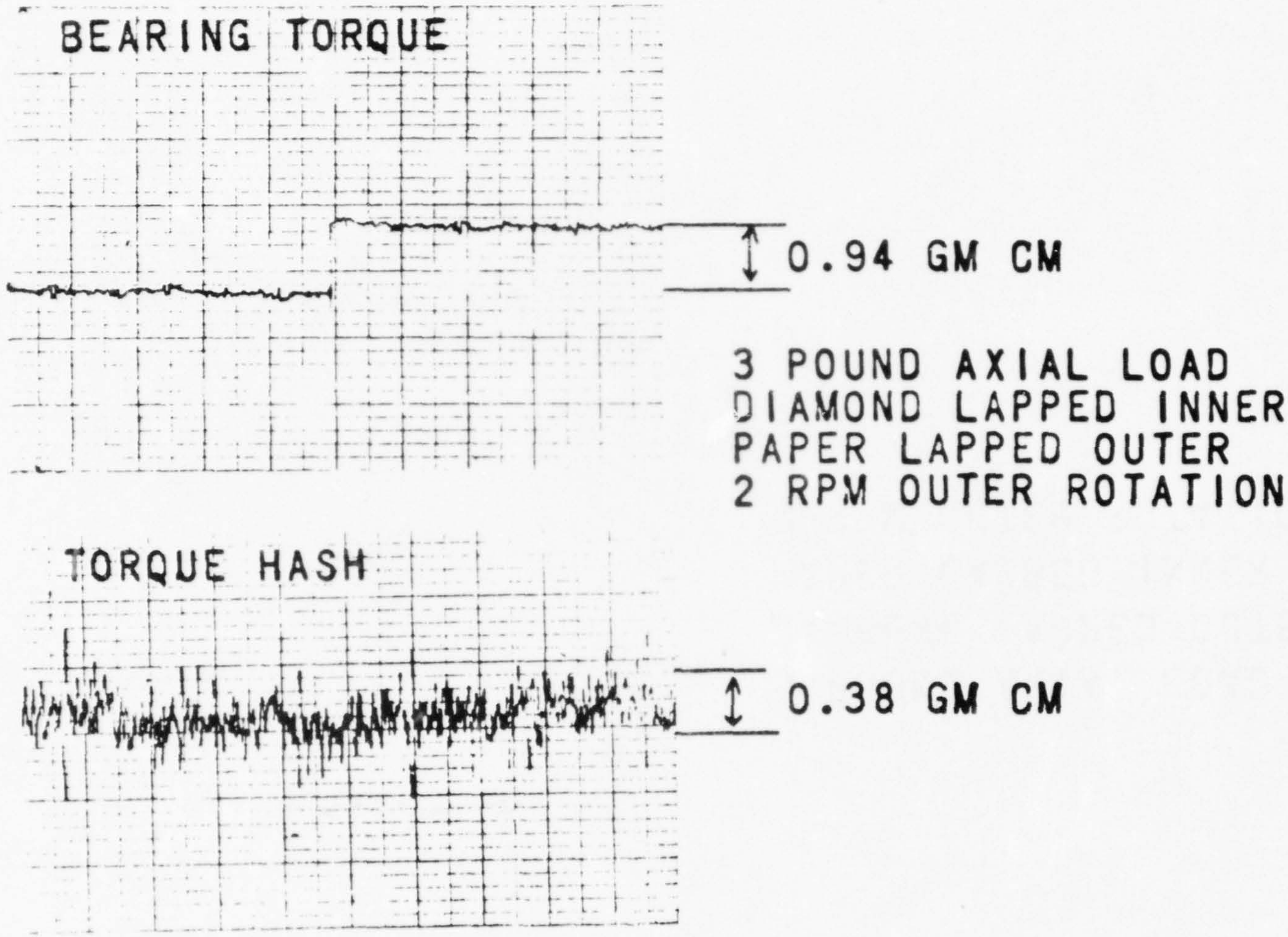


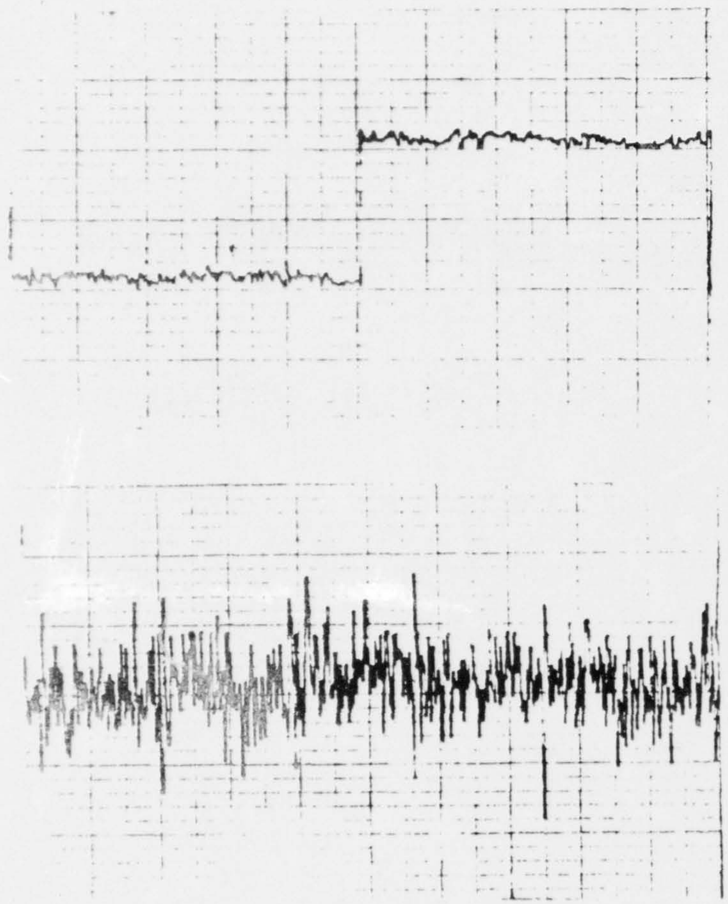
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER

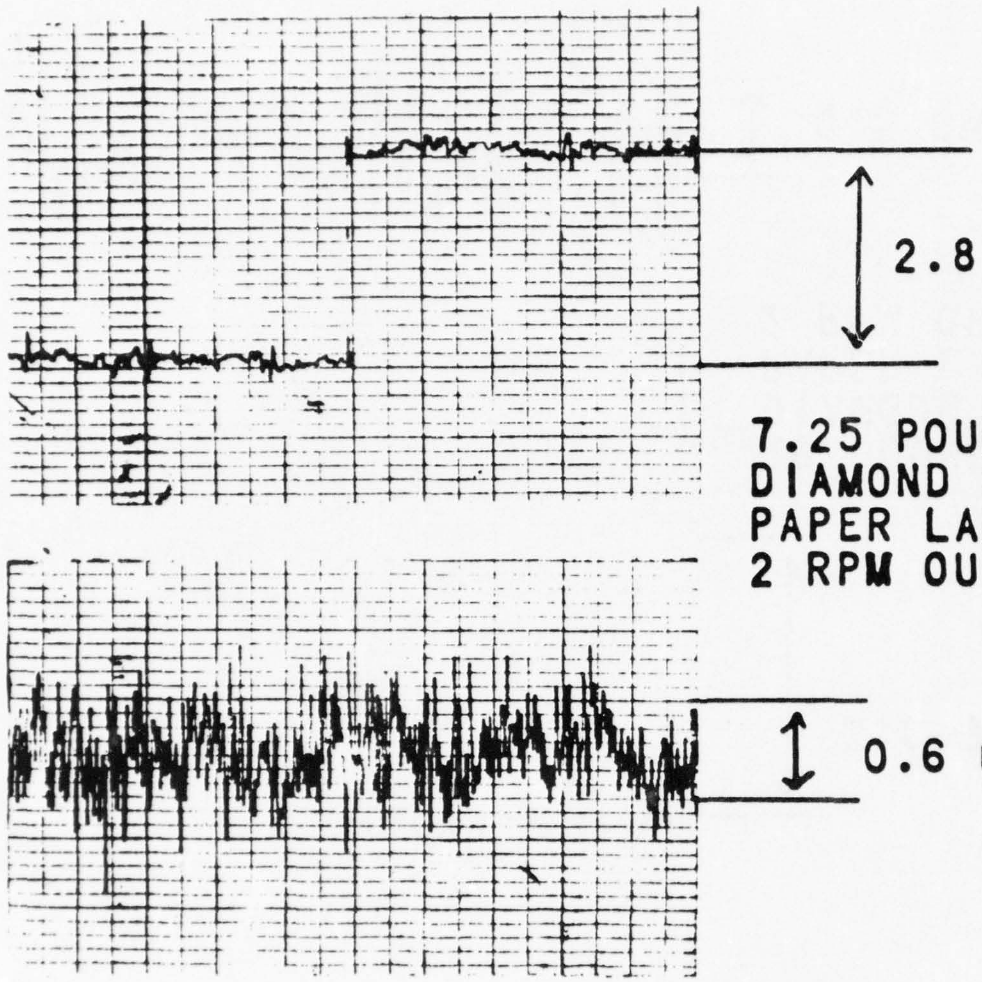


5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

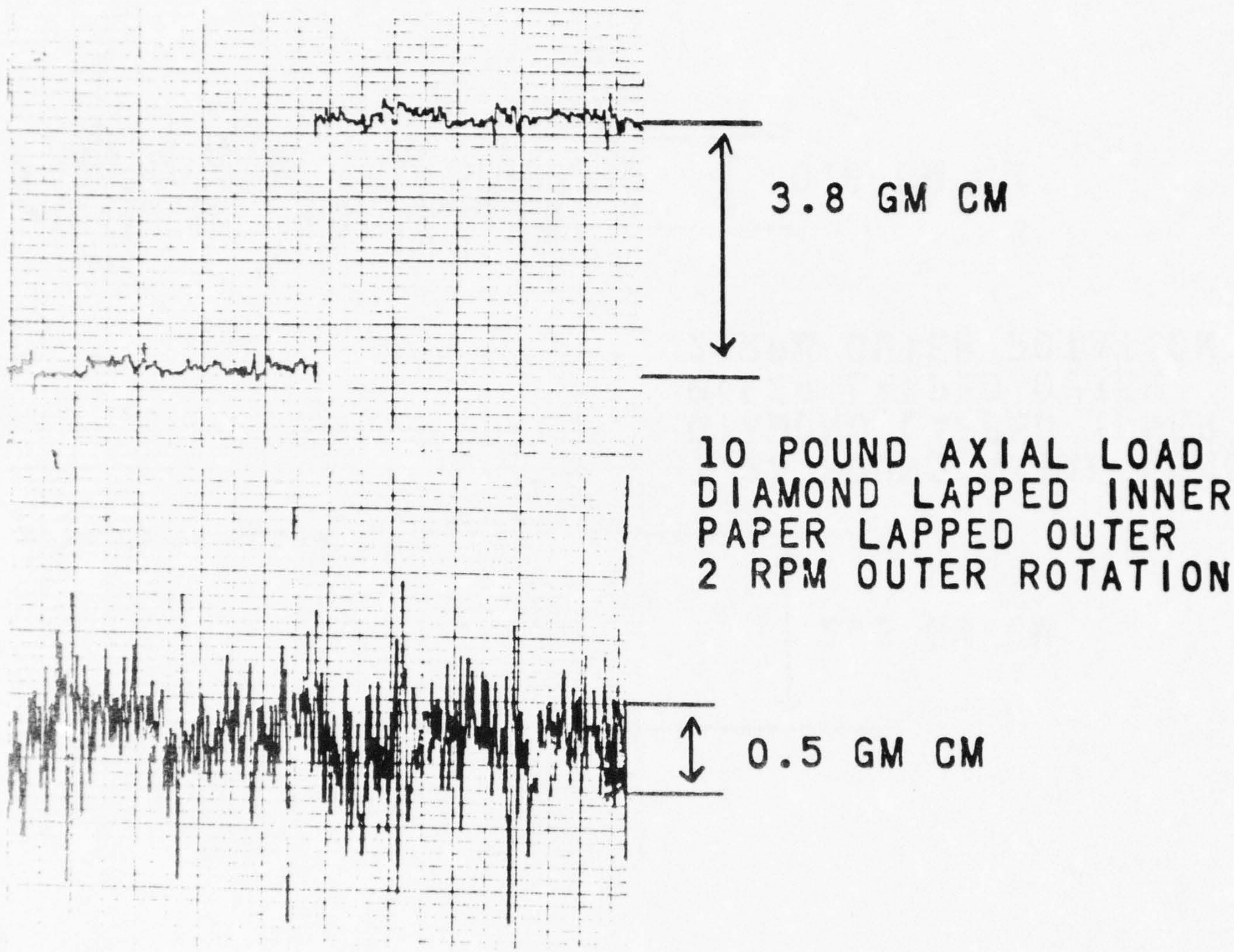

BEARING TORQUE
0.94 GM CM
3 POUND AXIAL LOAD
DIAMOND LAPPED INNER
PAPER LAPPED OUTER
2 RPM OUTER ROTATION
TORQUE HASH
0.38 GM CM

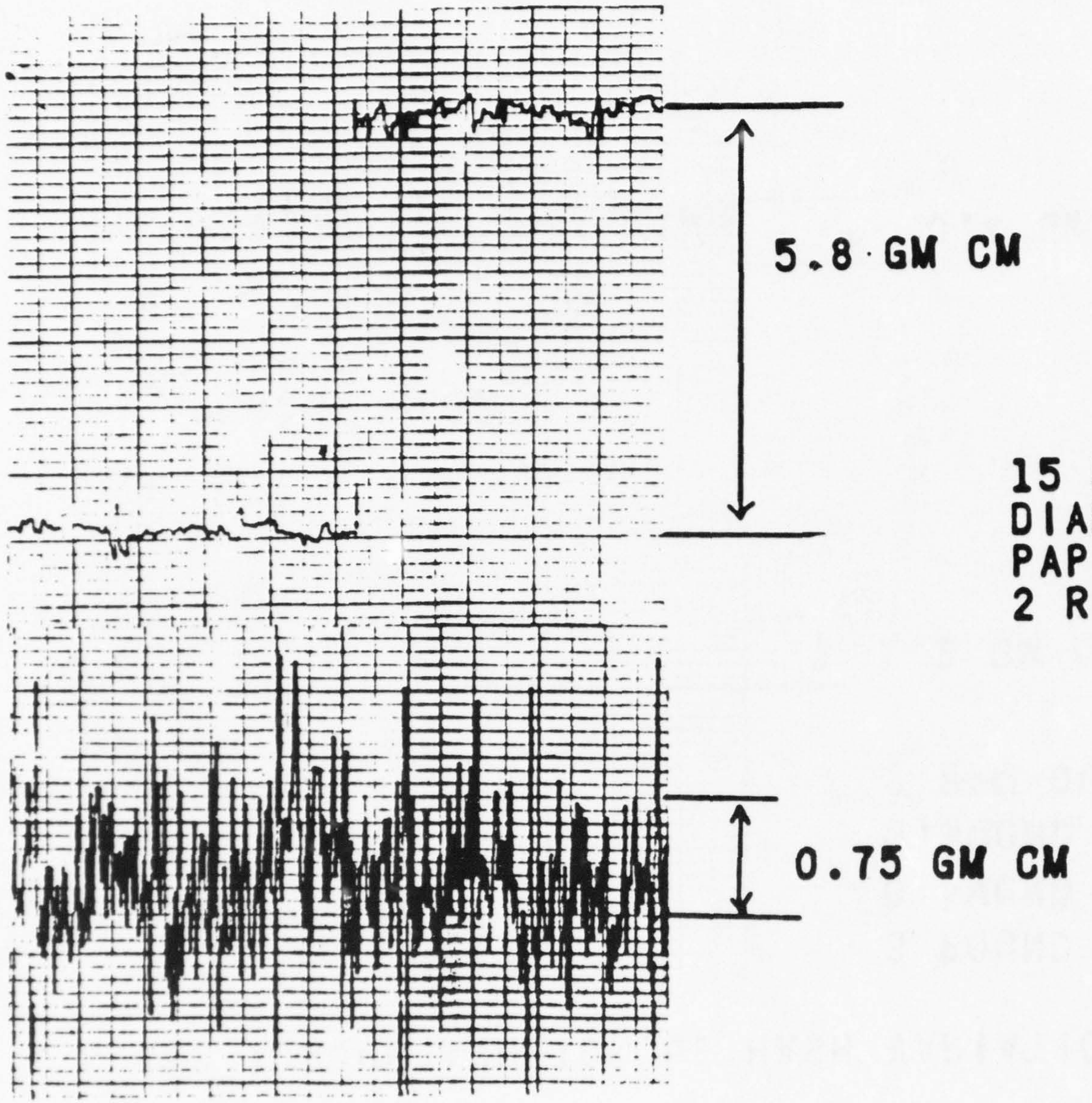


5 POUND AXIAL LOAD
DIAMOND LAPPED OUTER
PAPER LAPPED INNER
2 RPM OUTER ROTATION



7.25 POUND AXIAL LOAD
DIAMOND LAPPED INNER
PAPER LAPPED OUTER
2 RPM OUTER ROTATION

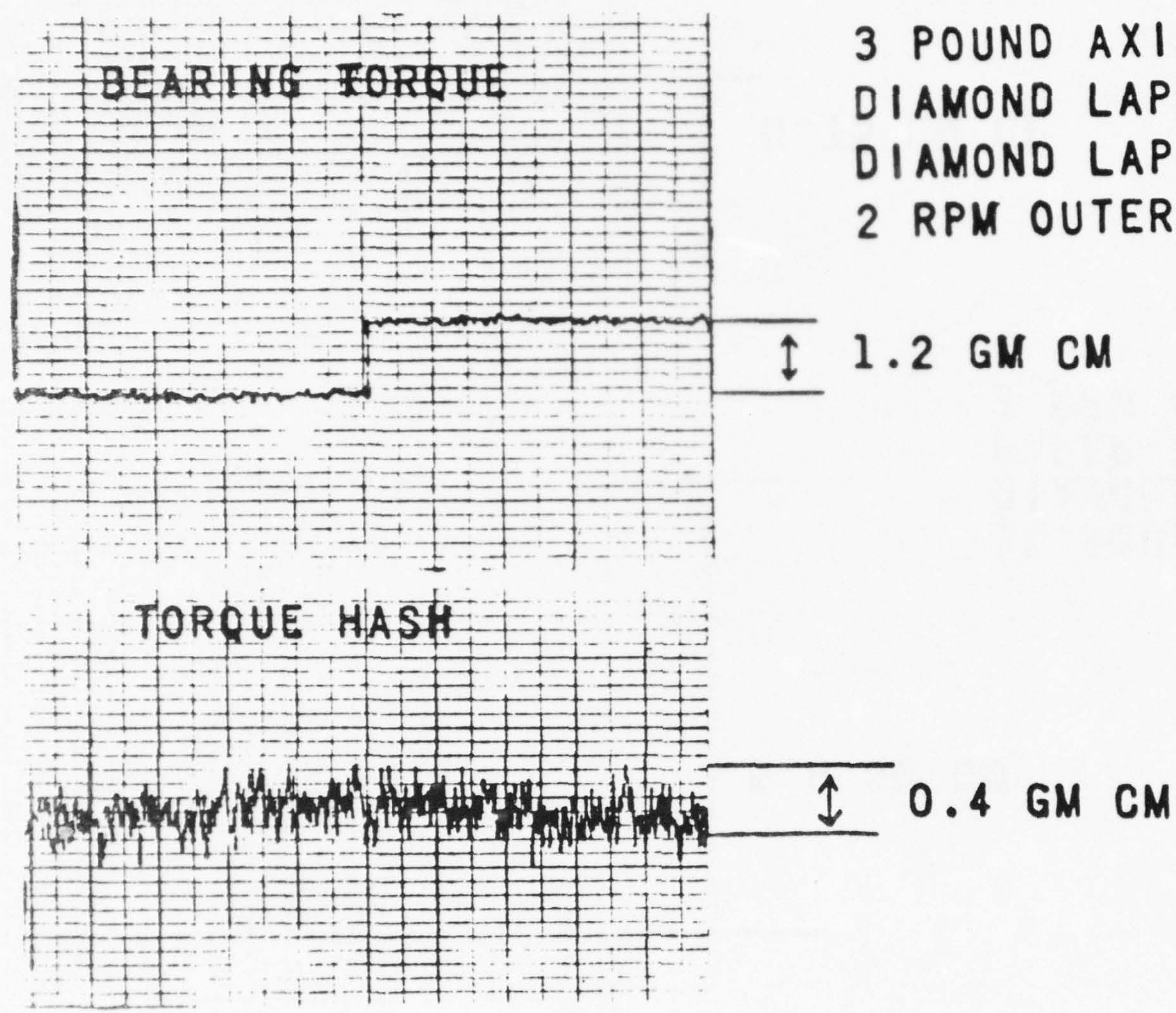

3.8 GM CM
10 POUND AXIAL LOAD
DIAMOND LAPPED INNER
PAPER LAPPED OUTER
2 RPM OUTER ROTATION
0.5 GM CM

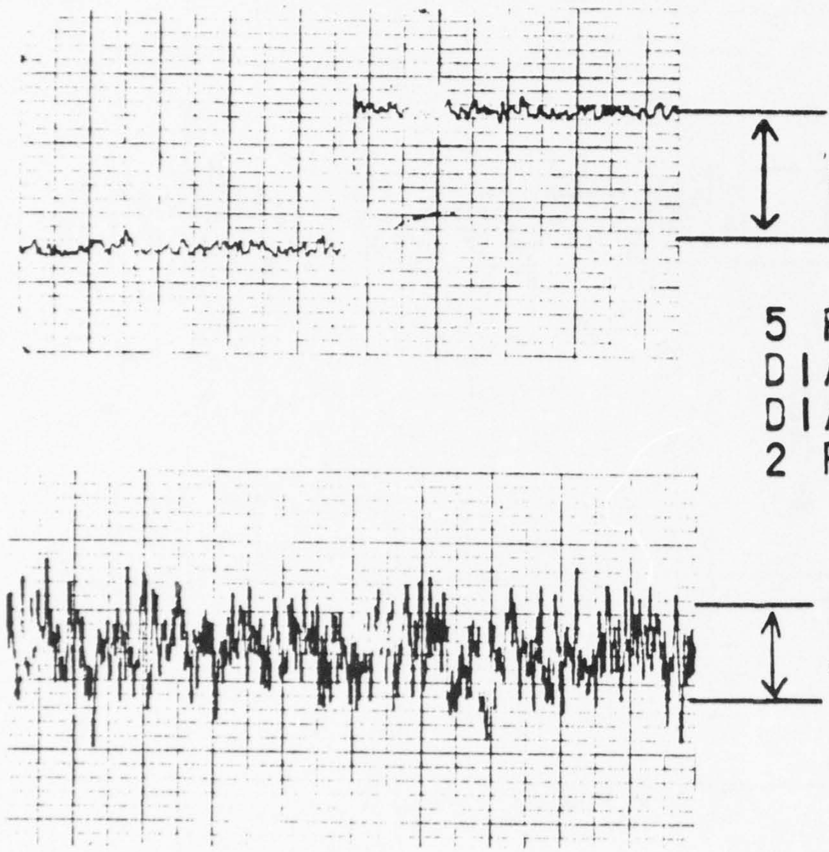


15 POUND AXIAL LOAD
DIAMOND LAPPED INNER
PAPER LAPPED OUTER
2 RPM OUTER ROTATION

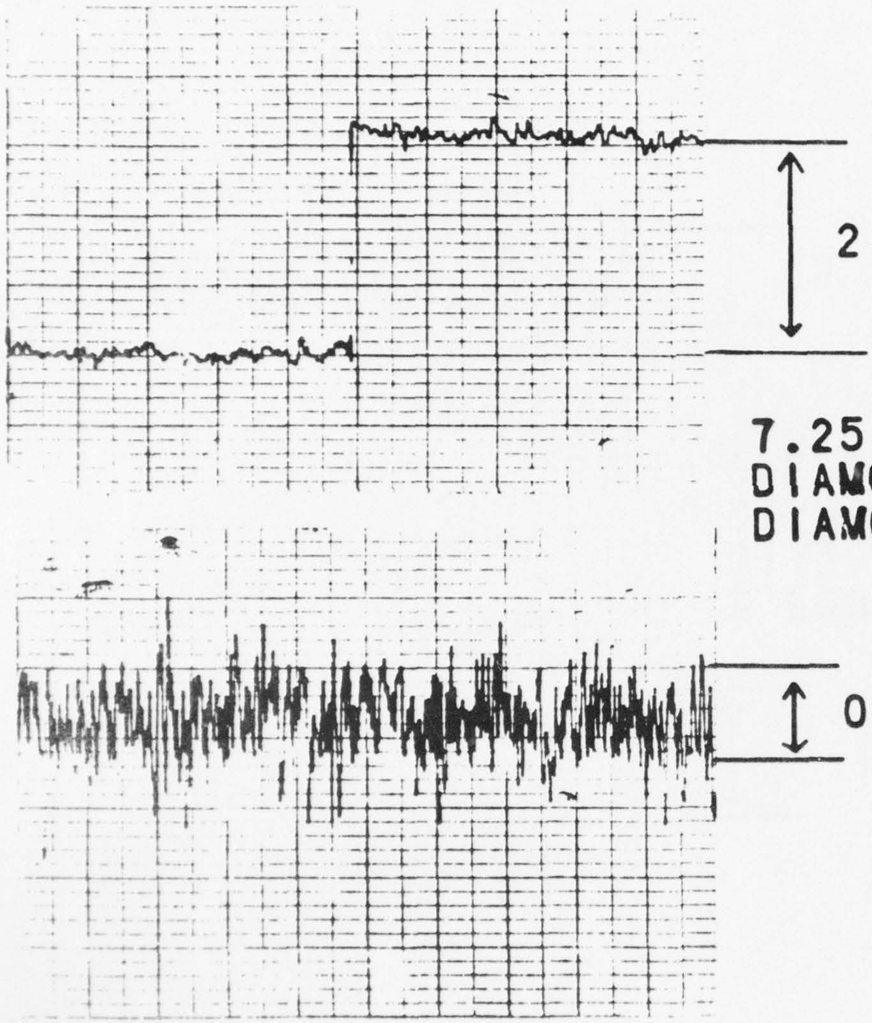
SR4SS TORQUE AND TORQUE HASH VARIATION WITH LOAD

3 POUND AXIAL LOAD
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER
2 RPM OUTER ROTATION

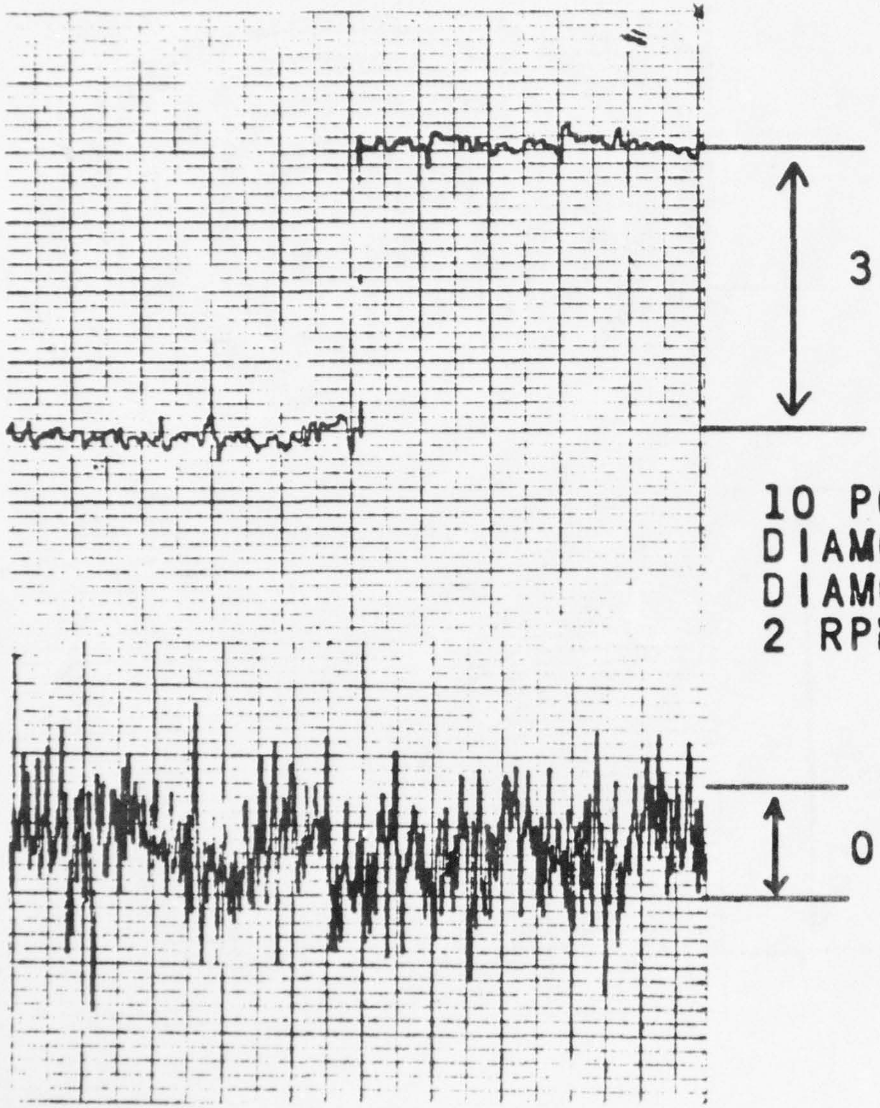




5 POUND AXIAL LOAD
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER
2 RPM OUTER ROTATION



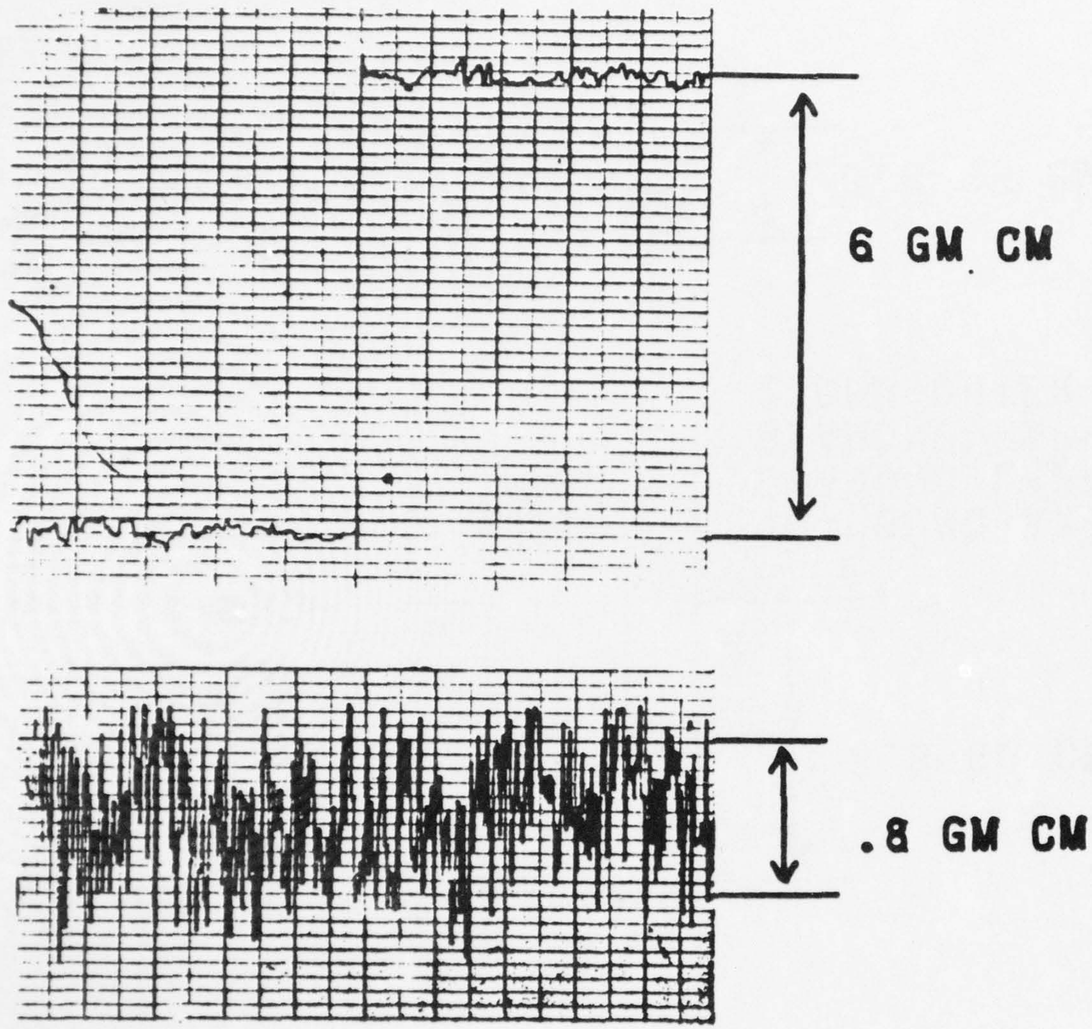
7.25 POUND AXIAL LOAD
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER



3.8 GM CM

10 POUND AXIAL LOAD
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER
2 RPM OUTER ROTATION

0.6 GM CM

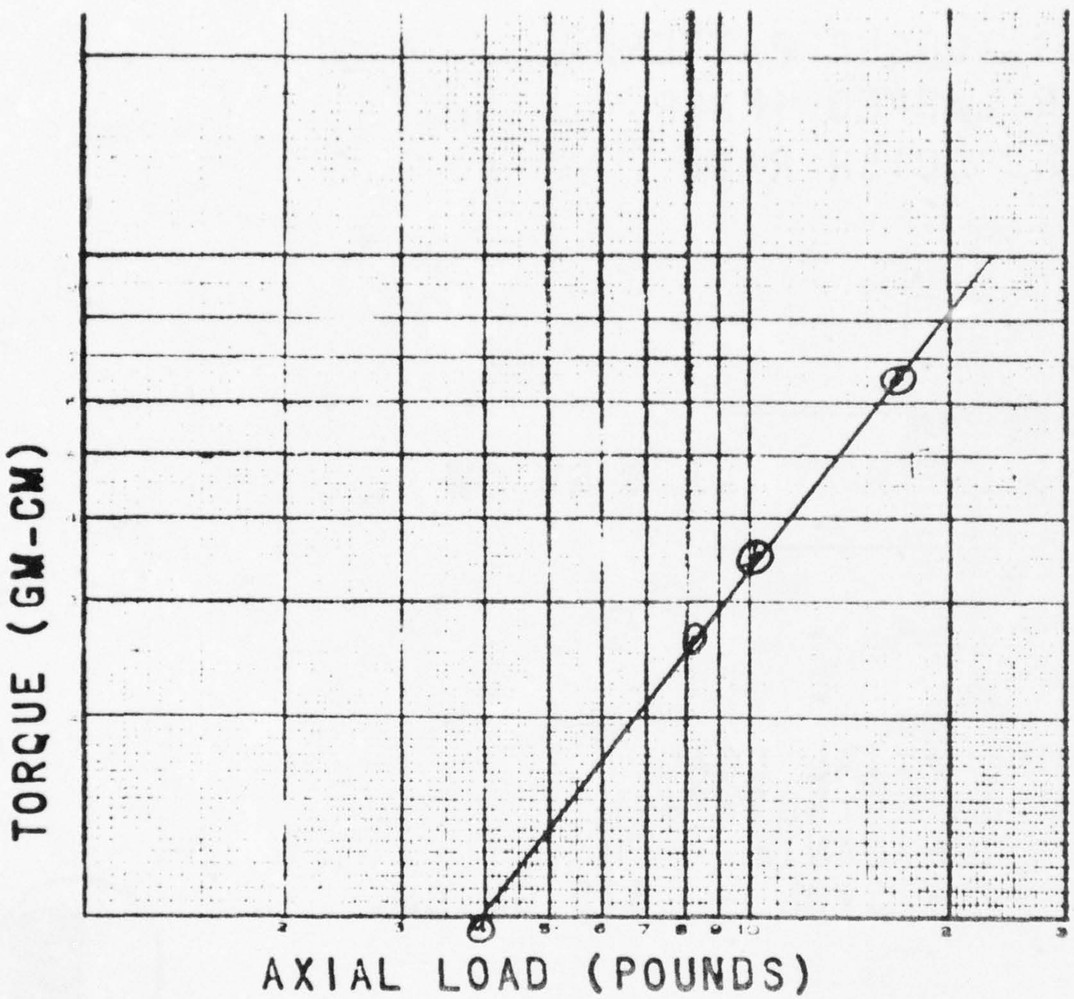


15 POUND AXIAL LOAD

DIAMOND LAPPED INNER

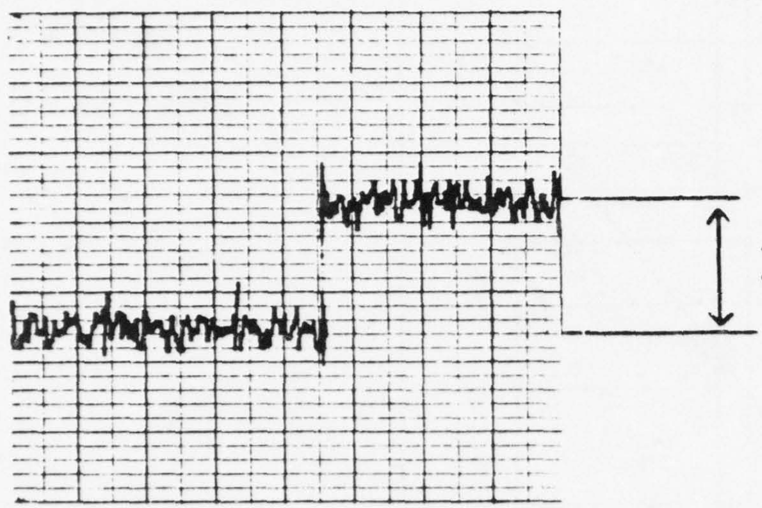
DIAMOND LAPPED OUTER

2 RPM OUTER ROTATION



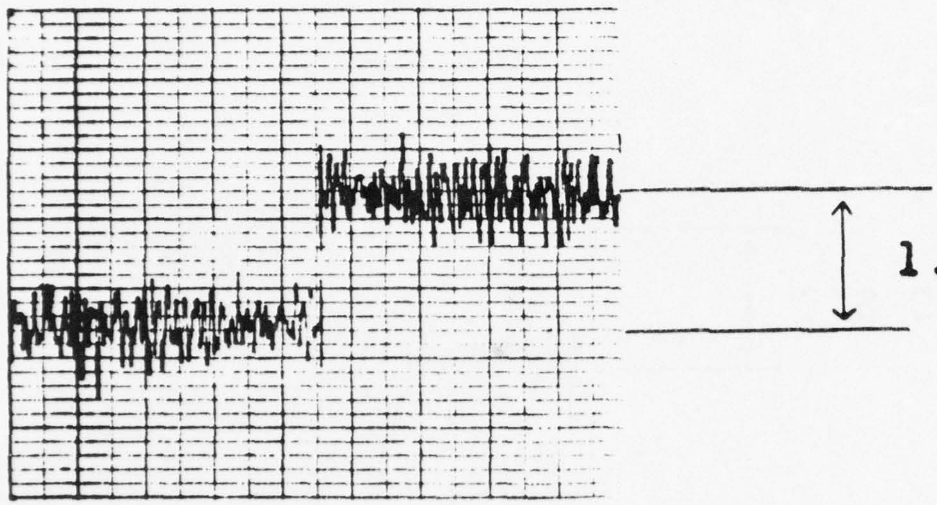
PLOT OF TORQUE
VERSUS
LOAD
SR4SS BEARING

SR4SS TORQUE PATTERN
PAPER LAPPED INNER
GROUND OUTER RACE



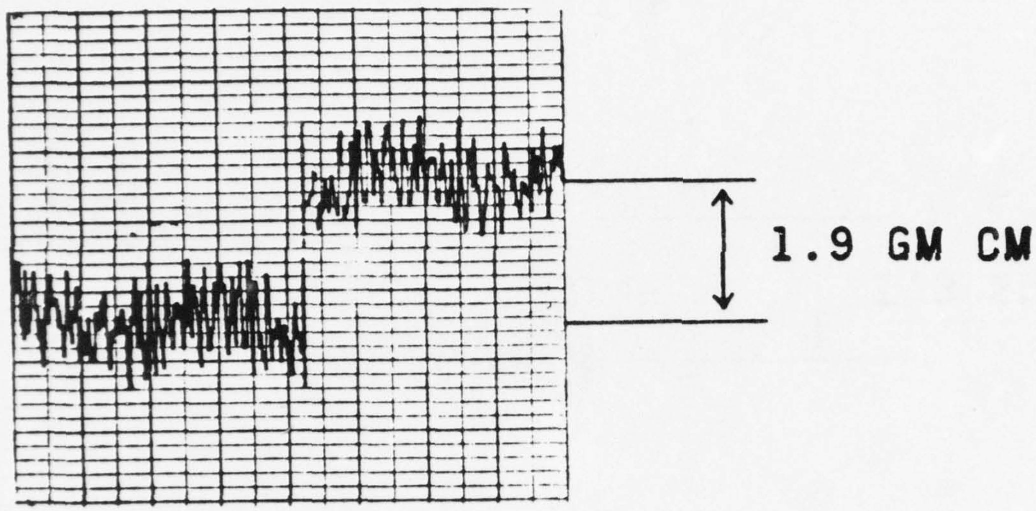
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
GROUND INNER RACE
PAPER LAPPED OUTER



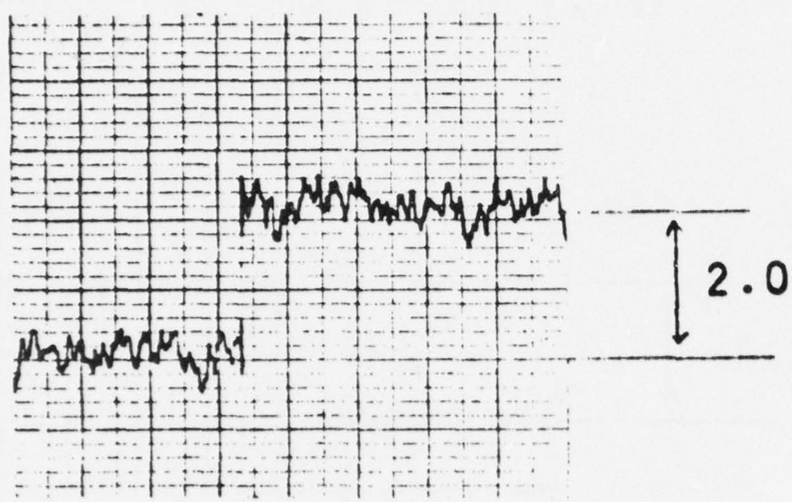
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
GROUND INNER RACE
DIAMOND LAPPED OUTER



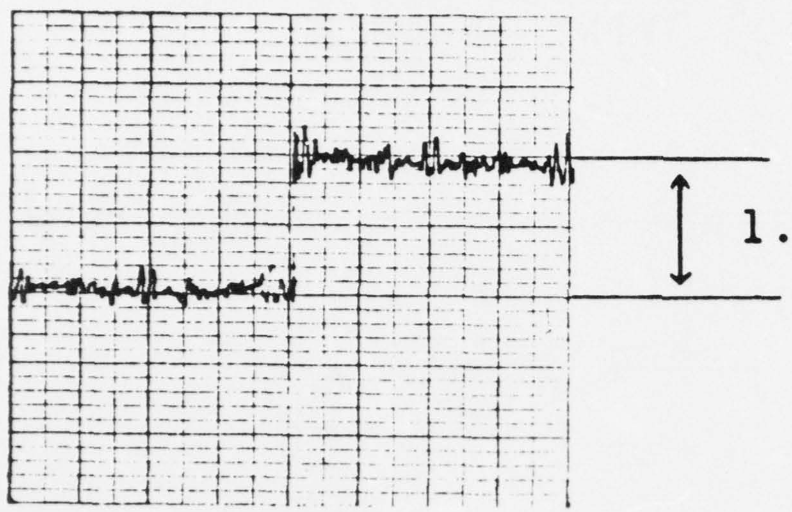
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
0-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
DIAMOND LAPPED INNER
GROUND OUTER RACE



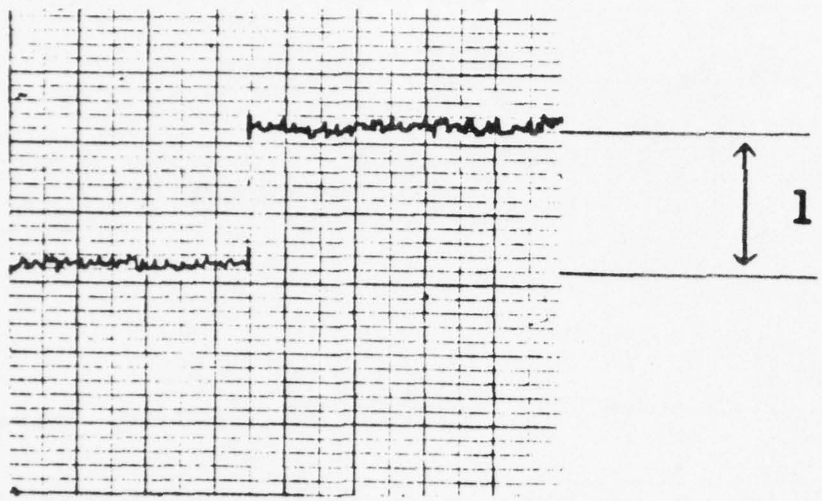
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
PAPER LAPPED INNER
DIAMOND LAPPED OUTER



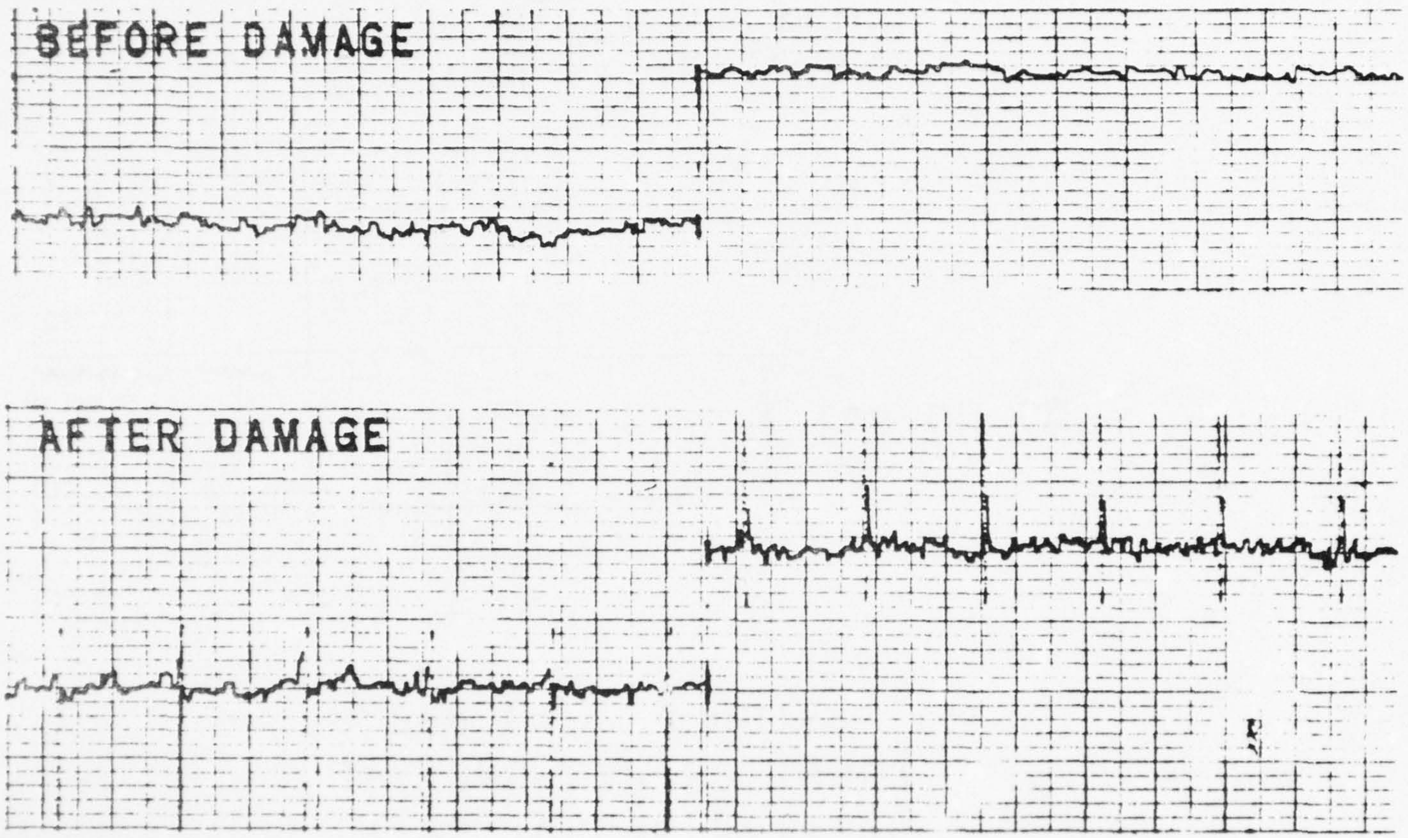
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
O-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

SR4SS TORQUE PATTERN
DIAMOND LAPPED INNER
PAPER LAPPED OUTER



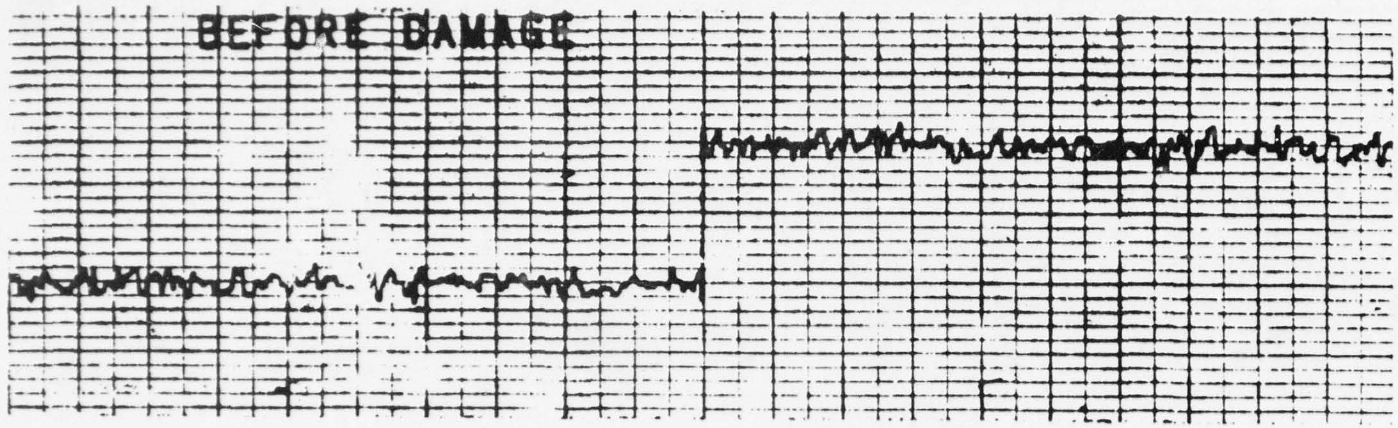
5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
0-11 LUBRICANT
MINOR DIVISION - .375 GM.CM.

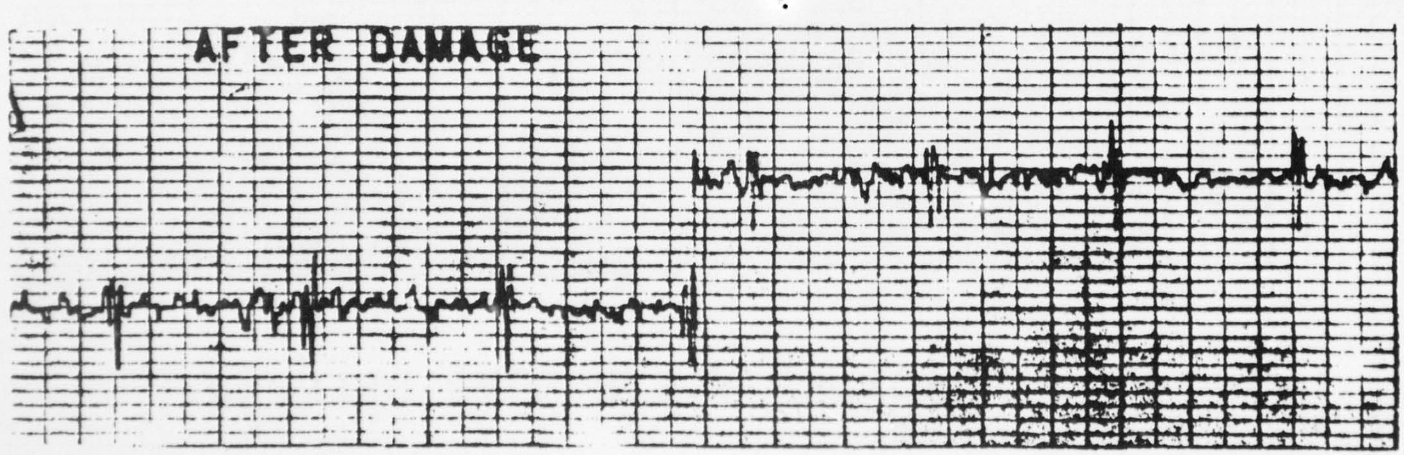
EXAMPLE OF EFFECT ON TORQUE PATTERN WHEN INNER RACE
HAS A DEFECT



5 POUND AXIAL LOAD
2 RPM OUTER ROTATION
PAPER SPEED 2MM/SEC

EXAMPLE OF EFFECT ON TORQUE PATTERN WHEN OUTER RACE HAS A DEFECT



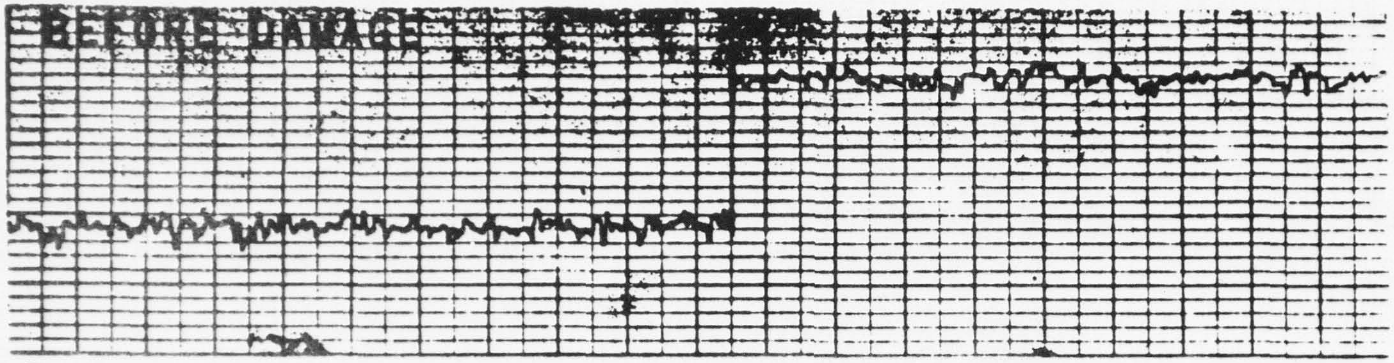


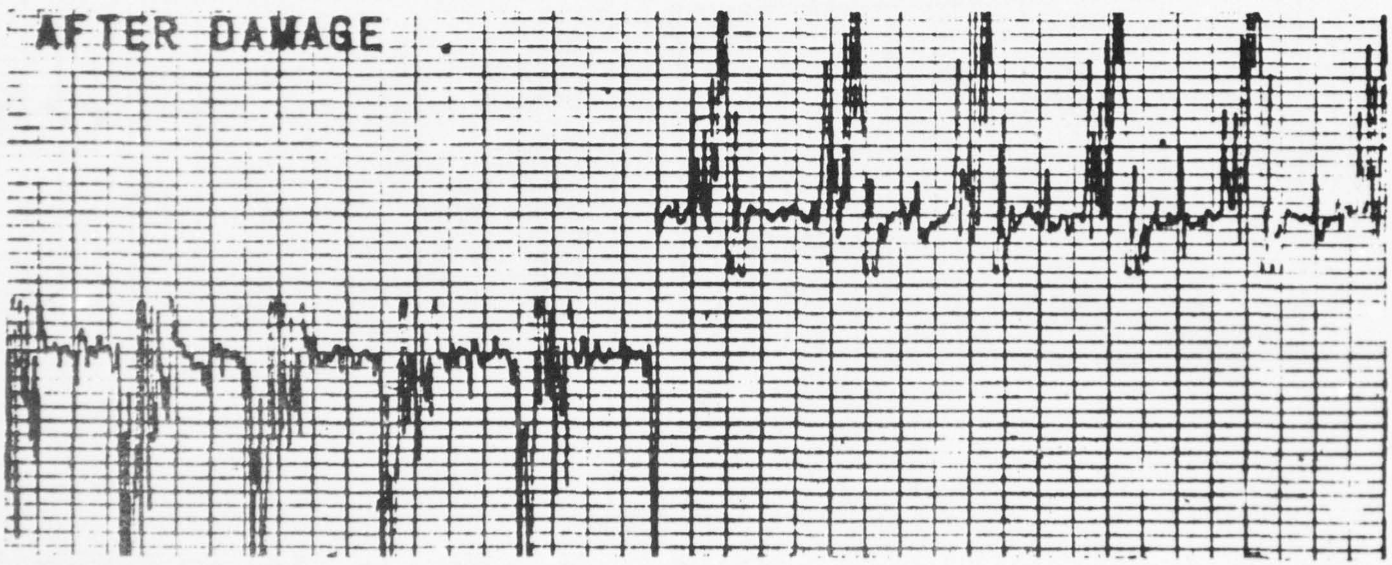
5 POUND AXIAL LOAD

2 RPM OUTER ROTATION

PAPER SPEED 2MM/SEC

[illegible] OF EFFECT ON TORQUE PATTERN WHEN THE BEARING BALL HAS A DEFECT





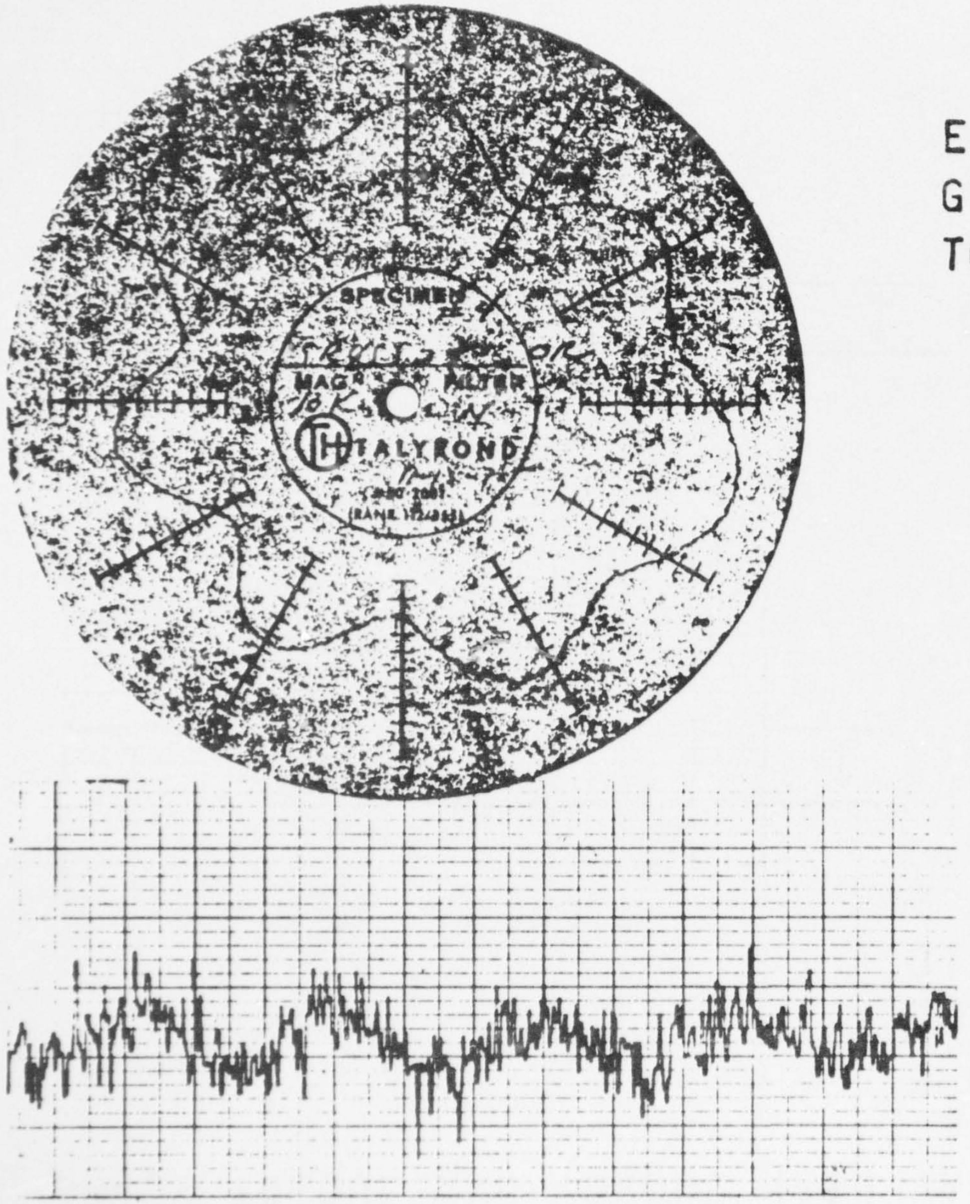
5 POUND AXIAL LOAD

8-3/32 BALLS

2 RPM OUTER ROTATION

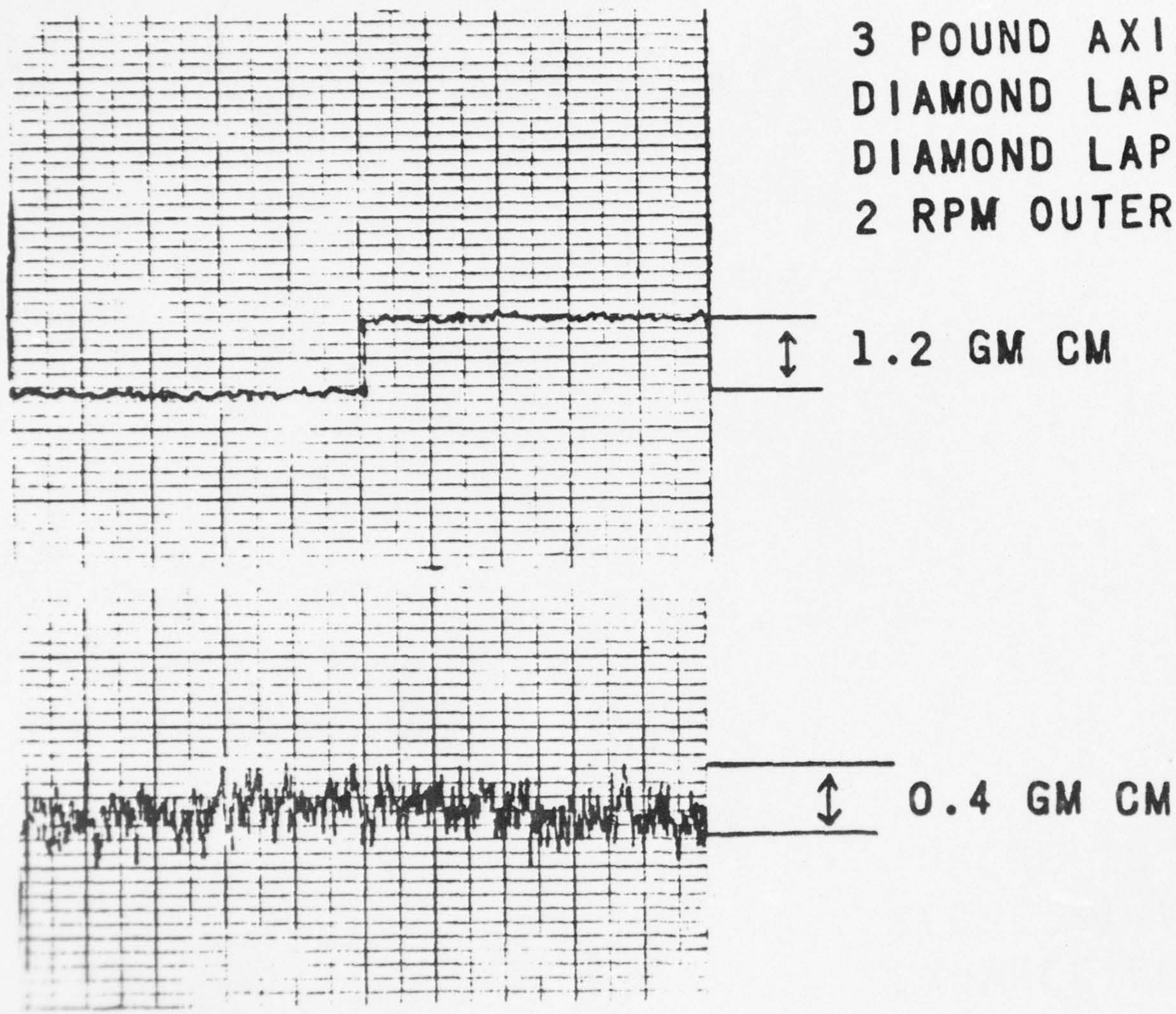
PAPER SPEED 2MM/SEC

EXAMPLE OF BEARING OUTER GEOMETRY AFFECTING THE TORQUE TRACE



SR4SS TORQUE AND TORQUE HASH VARIATION WITH LOAD

3 POUND AXIAL LOAD
DIAMOND LAPPED INNER
DIAMOND LAPPED OUTER
2 RPM OUTER ROTATION



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DATA EXCHANGE FOR INERTIAL SYSTEMS (9TH), CONFERENCE PROCEEDING--ETC(U)
SEP 76 E T BODEM
UNCLASSIFIED AGMC-XRX-76-5 NL

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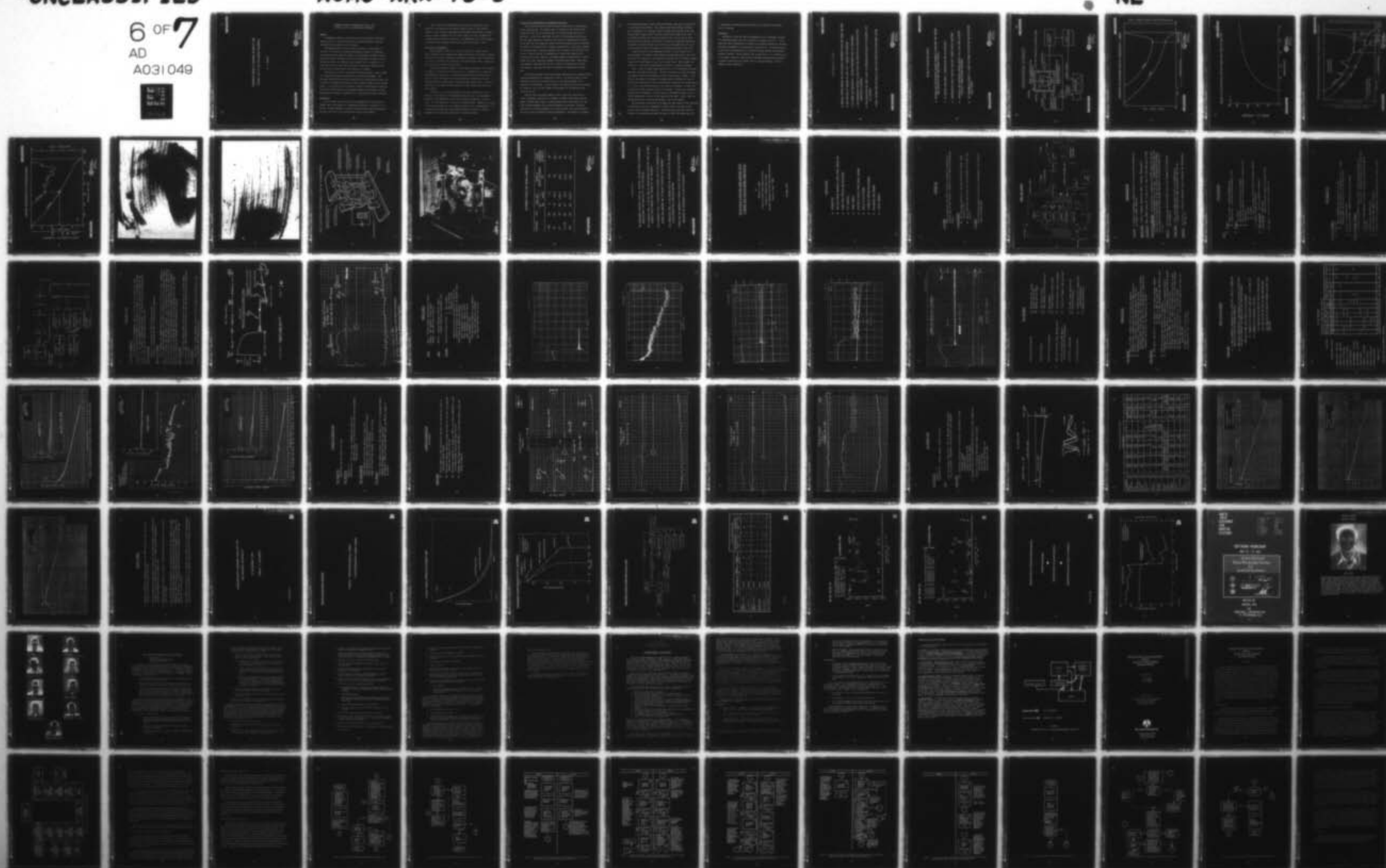

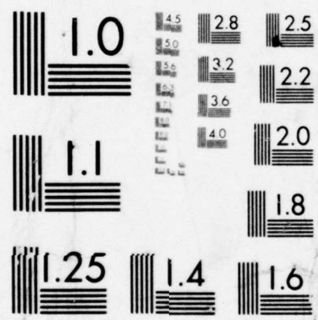

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

UNCLASSIFIED

DYNAMOMETER METHOD TO DETERMINE RELIABILITY AND RESIDUAL LIFE OF GAS SPIN BEARING INSTRUMENTS

L. J. Blache

DYNAMOMETER METHOD TO DETERMINE RELIABILITY AND RESIDUAL LIFE OF GAS-SPIN-BEARING INSTRUMENTS

Summary

A dynamometer method is described by which the coastdown torque-speed characteristics of a gas-spin bearing are accurately measured to provide information on the condition of the bearing.

This method provides a means by which variation in torque about the spin axis of a bearing is accurately measured and recorded. By comparing the torque and rotor speed with respect to time during a coastdown, selected bearing performance parameters can be used to determine the condition of the bearing and, hence, its reliability and residual life. In practice, it is found that the lower speed region just prior to and during setdown provides the most accurate indication on the condition of a bearing.

The method can be used at the wheel-build stage through to final assembly for screening and diagnostic purposes and for bearing development. The instrument described has been used successfully for evaluating both single- and two-degree-of-freedom-gyro bearings at both the wheel-assembly and top-assembly stages. It has proven to be consistently reliable in evaluating the condition of gas-spin bearings based on the subsequent diagnostic disassembly of these bearings and has become an invaluable tool to help improve bearing reliability.

Introduction

Slide 1 defines the basis on which the dynamometer test constitutes an integral part of the process for determining reliability or residual life of a bearing. Although emphasis is placed on the evaluation of gas-spin bearings, any other type of precision bearing can be tested in this manner.

Slide 2 shows that contamination or scoring in a bearing will cause asperities to protrude from the bearing surface so that, as the rotating element or rotor gradually approaches the stationary element during coastdown, spurious torques in addition to the viscous torque will occur the moment the rotating element touches the asperities. The dynamometer senses these torques and displays them, together with the rotor speed, with respect to time.

Description of Dynamometer

The dynamometer, Slides 3, 10, and 11, consists of a large circular gimbal supported by two diametrically opposed hydrostatic gas bearings, together with associated pickoff electronics and torquers required to cage the gimbal and to provide a sensitive chart recording of the gimbal caging torque. Supporting electronics are not shown in these slides.

The gas-bearing wheel assembly, or the complete instrument to be evaluated, is mounted in the gimbal with the spin axis, or a component of it, alined with the dynamometer output axis. Electronics to power the gyro spin motor and to provide a chart recording of the rotor speed during coastdown are included. A self-generating or external means of measuring wheel speed is used. Electrical connections to the wheel are made through flex leads between the gimbal and a fixed element.

In Slide 12, a TGG (Third-Generation Gyro) wheel assembled in a test housing is shown mounted in the dynamometer and under test. The dynamometer is operated at room temperature inside a draft shield and mounted on a granite stand. It can be mounted in a vertical or horizontal mode. Damping of the system is achieved electrically and the frequency response is up to approximately 10 Hz. To reduce the back EMF drag torque during coastdown, the rotor is initially demagnetized by wiping down automatically by capacitive means.

Evaluation and Interpretation of Dynamometer Test Data

Slide 4 shows the typical speed and torque characteristics obtained with a new, clean bearing. The caging torque is a measure of the viscous torque between the rotor and the stationary part of the bearing when the rotor is gas-borne. As the rotor slows down, the lift of the bearing decreases along with the drag torque until transition from viscous to sliding friction occurs. At the same time, the exponential speed curve goes through a point of inflection. The transition from gas-borne to sliding is chacterized by a low-noise, smoothly curving torque trace reaching a maximum, then returning to zero with the rotor at rest. When the bearing is contaminated or scored, the torque trace is characterized by noisy, spurious, and abrupt changes in torque which, if large enough, will cause significant changes in the wheel-speed slope. These tests are frequently conducted with spin axis vertical or along the axis of least load capacity, since this will tend to accentuate the conditions of bearing wear.

By having a knowledge of the bearing wheel speed/bearing lift characteristics, obtained experimentally or analytically, Slide 5, the speed at which a torque disturbance occurs can be related directly to the apparent height of the asperities in the bearing. The true height of the asperities can only be deduced by inference, since this will depend on the geometry of the bearing and the direction of lift.

From the torque and speed readings, Slide 6, the first indication of a torque disturbance, deceleration at setdown, coastdown time between selected speeds, minimum torque, speed at minimum torque, power, drag coefficient, and other related parameters can be readily measured or calculated. The first indication of a torque disturbance is of prime interest, since this represents the first positive indication of bearing degradation. The height of an asperity

or minimum bearing gap at which a torque disturbance takes place is equivalent to a particular acceleration. Thus, under a launch acceleration situation, due to compliance of the bearing, erratic torques can be exerted on the rotor during flight if debris peaks are within the deflection range of the rotor. It is therefore important that the start-stop wear rate, and the rate at which debris builds up, should be sufficiently low that the accumulation through the instrument and system checkout, up to the time of field operation, will still allow a margin of safety with respect to the launch deflection of the rotor.

Torque resolution of the dynamometer depends to a great extent on the overall weight of the gimbal, wheel assembly, and mounting fixture, since this will affect the clearance in the hydrostatic bearings with its attendant turbine torque effects which appear as noise in the torque trace. Under minimal load conditions, a resolution of approximately 10 dyne-cm is normally obtained.

Slide 7 shows the speed-torque characteristics of a contaminated Autonetics G6B4 gyro, with spin axis vertical. The first occurrence of torque disturbance corresponds to asperities measuring at least 140 microinches in height. Since the gyro incorporates a two-degree-of-freedom spherical bearing, the cause of the spurious torque could be due to contamination located near the bearing poles, i.e., close to the vertical spin axis, or closer to the equator, in which case the asperities would be greater than 140 microinches. The gyro was subsequently diagnostically disassembled. Slide 8 shows the contamination found in one of the two hemispherical cavities in the region of a pad area. Slide 9 shows the contamination found on the nonrotating ball, close to the equator.

With experience, predictions can be made with some accuracy on the condition of a bearing in terms of contamination, surface finish or scoring, and the location of the resultant asperities. The method allows very small spurious torques to be detected and recorded, too small to affect the speed trace, but

of considerable significance when evaluating the reliability and residual life of a bearing.

Conclusions

Experience to date has shown the dynamometer to be consistently reliable for evaluating bearing condition in different instruments, Slide 12. It has shown that where contamination or scoring of the bearing surfaces was indicated, subsequent disassembly of the bearing has confirmed this. For design purposes, it has been of considerable use for comparing bearing surfaces with different boundary lubricants, bearing geometry, and surface finish. As a screening tool, it has helped isolate the cause for poor instrument performance and establish the means of predicting the residual life of a gas-spin bearing. Slide 13 summarizes these capabilities.

INTRODUCTION

- INERTIAL SYSTEMS REQUIRE GAS SPIN BEARING INSTRUMENTS WHICH ARE HIGHLY RELIABLE
- HIGH RELIABILITY DEPENDS ON LONG LIFE - TROUBLE FREE BEARINGS
- TO INSURE HIGH RELIABILITY, BEARING PERFORMANCE MUST BE PREDICTABLE
- THE DYNAMOMETER PROVIDES A QUALITATIVE AND QUANTITATIVE EVALUATION ON THE CONDITION OF A BEARING
- THIS EVALUATION CAN FORM A GUIDE IN DETERMINING RELIABILITY OR RESIDUAL LIFE OF A BEARING
- SUCH A METHOD COULD BE USED AS A BASIS FOR DETERMINING MAINTENANCE ACTION

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METHOD OF EVALUATING BEARING

- RELIABLE GAS SPIN BEARINGS REQUIRE PERMANENT CLEANLINESS AND FREEDOM FROM ASPERITIES AND OTHER SURFACE DEFECTS
- TO CONFIRM CLEANLINESS, CONTAMINATION MUST BE DETECTABLE
- CONTAMINATION CAUSES SPURIOUS SPIN-AXIS TORQUES DURING COASTDOWN
- ASPERITIES AND PROTRUDING SURFACE DEFECTS WILL ALSO CAUSE SPURIOUS SPIN-AXIS TORQUES DURING COASTDOWN
- THE DYNAMOMETER METHOD IS A SENSITIVE MEANS OF DETECTING AND DISPLAYING THESE TORQUES

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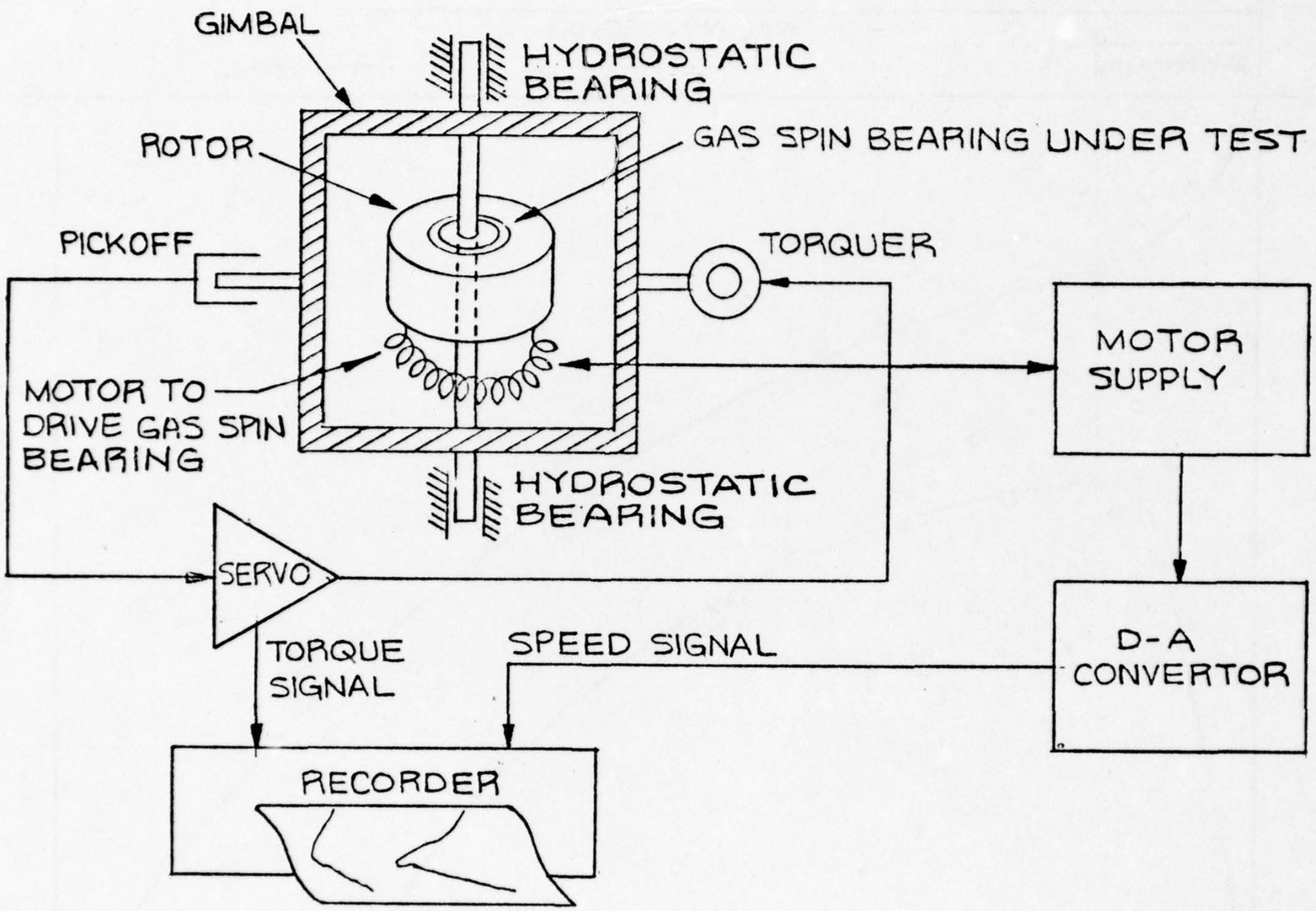
DYNAMOMETER SCHEMATIC



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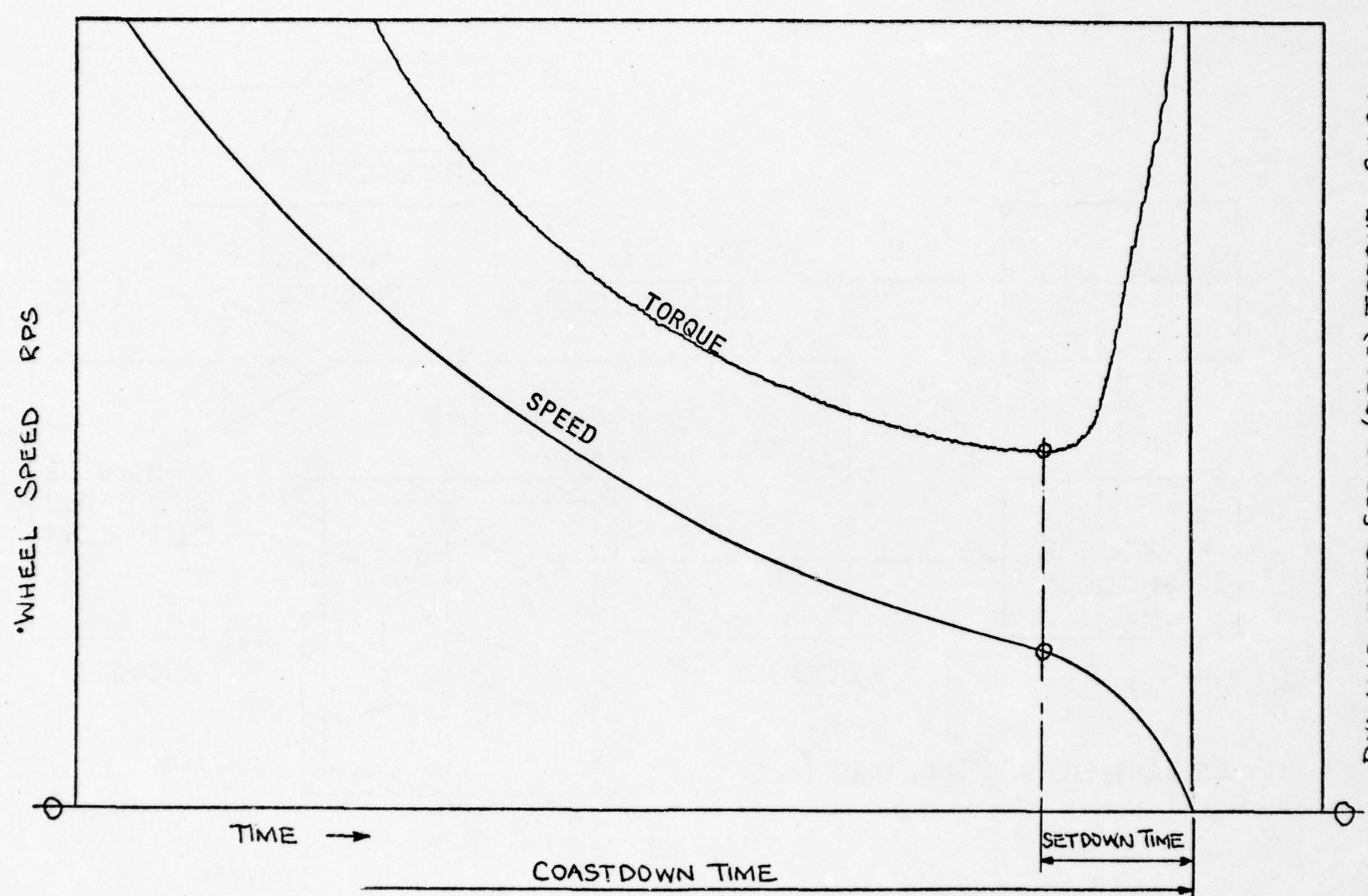
DYNAMOMETER GAS-SPIN BEARING COASTDOWN CHARACTERISTICS - GENERAL



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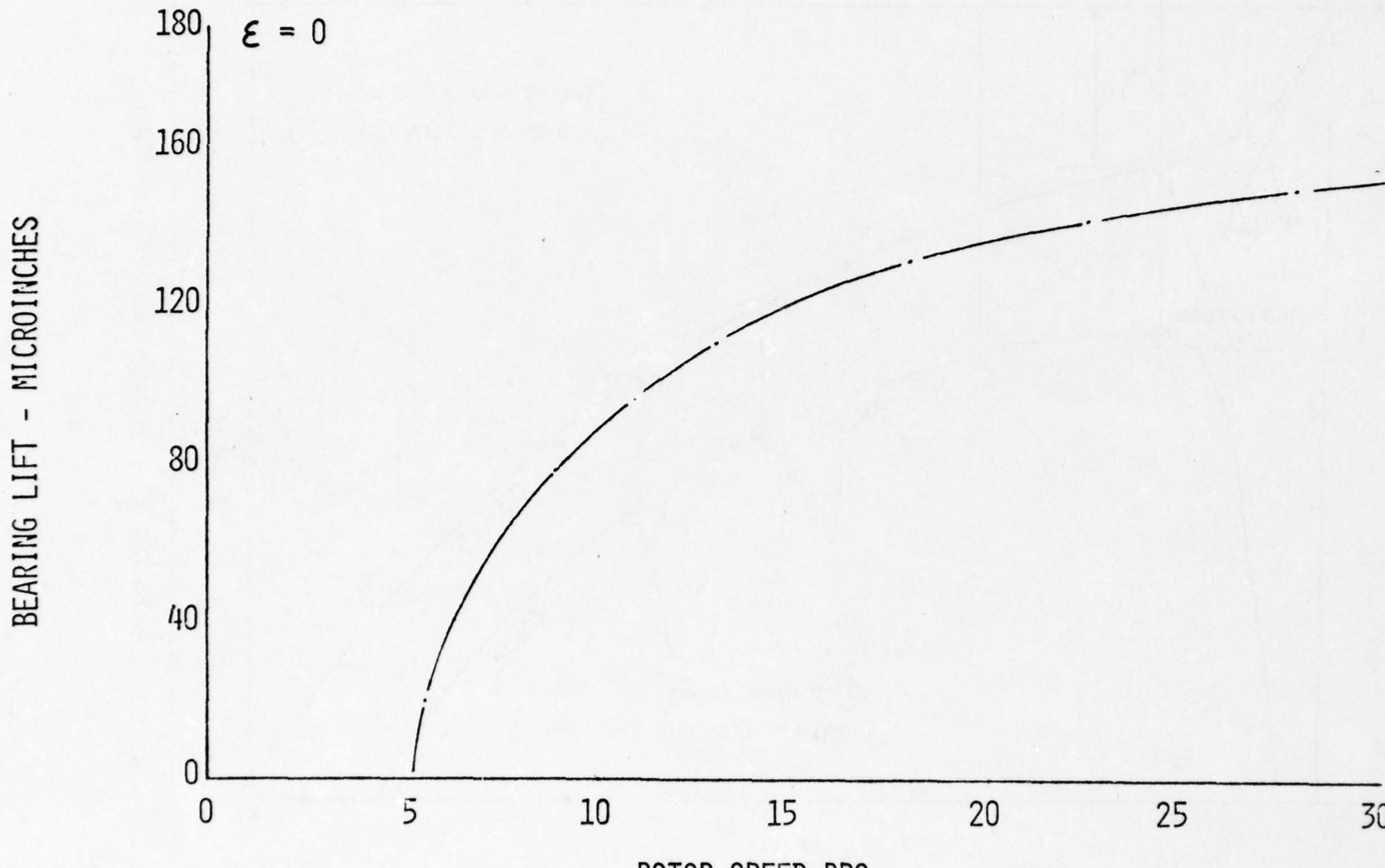
BEARING LIFT WITH SPIN AXIS VERTICAL VERSUS WHEEL SPEED FOR G6B4 GYRO



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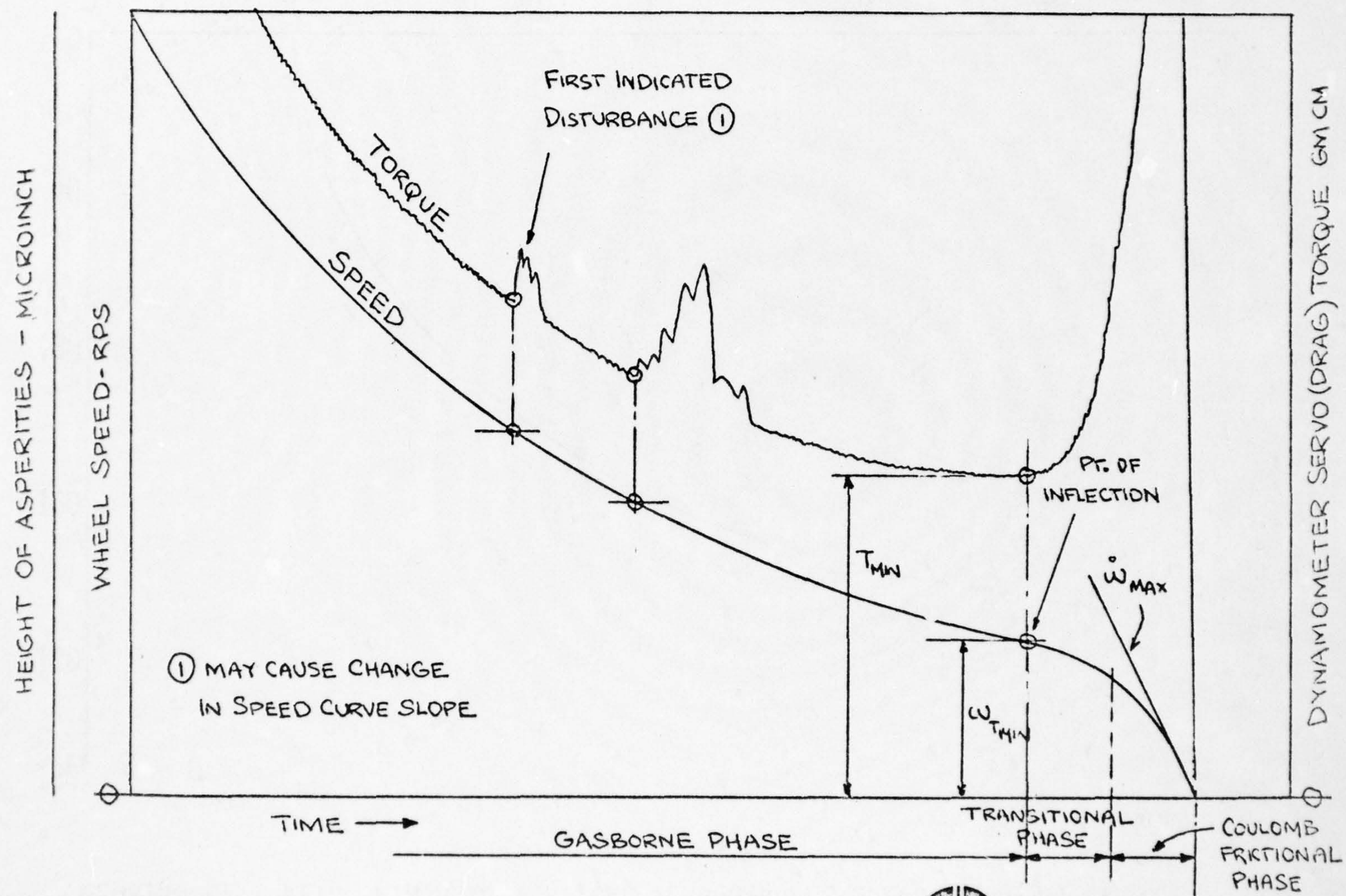
DYNAMOMETER GAS SPIN BEARING COASTDOWN CHARACTERISTICS — DETAILED



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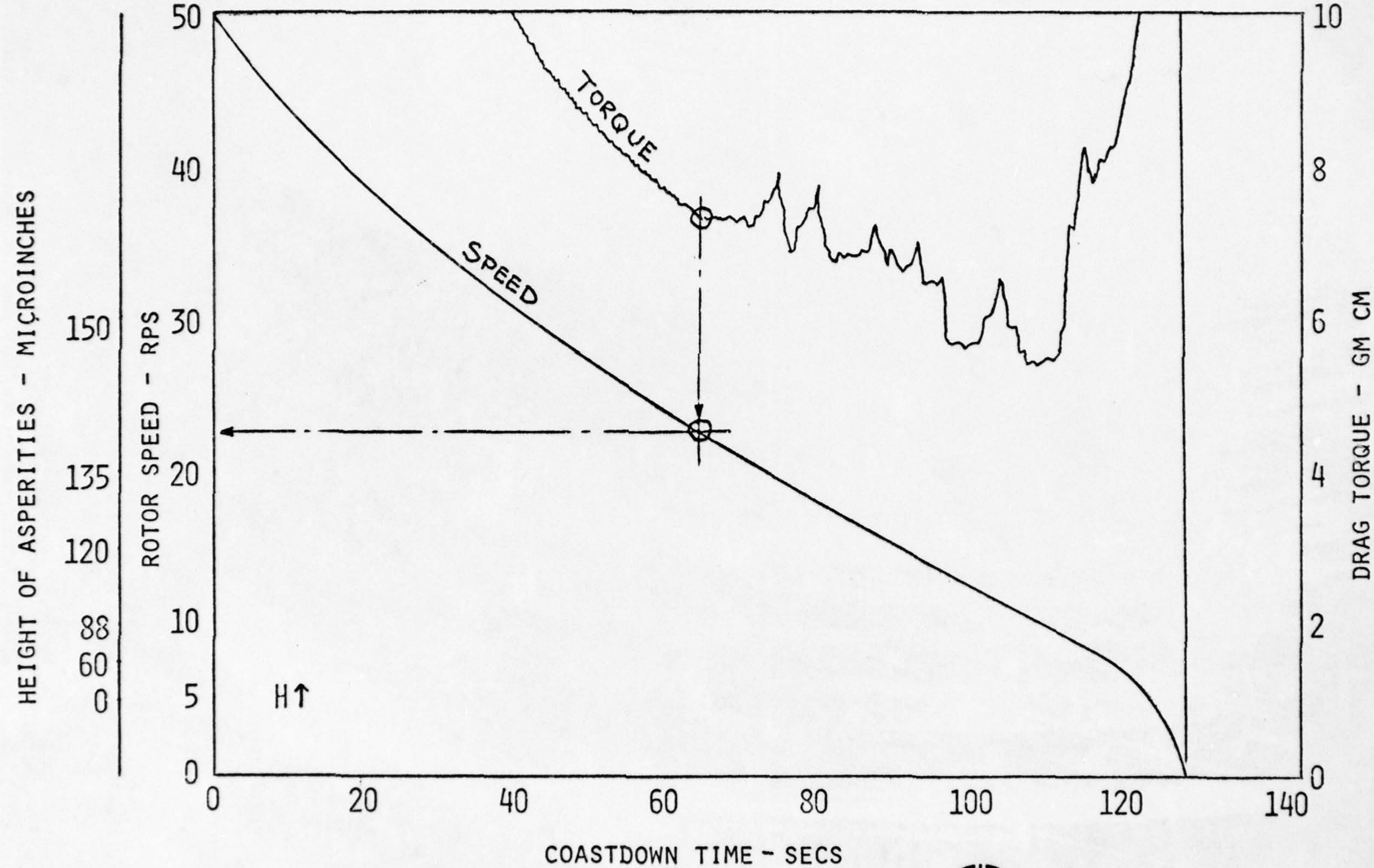
COASTDOWN CHARACTERISTICS OF CONTAMINATED BEARING



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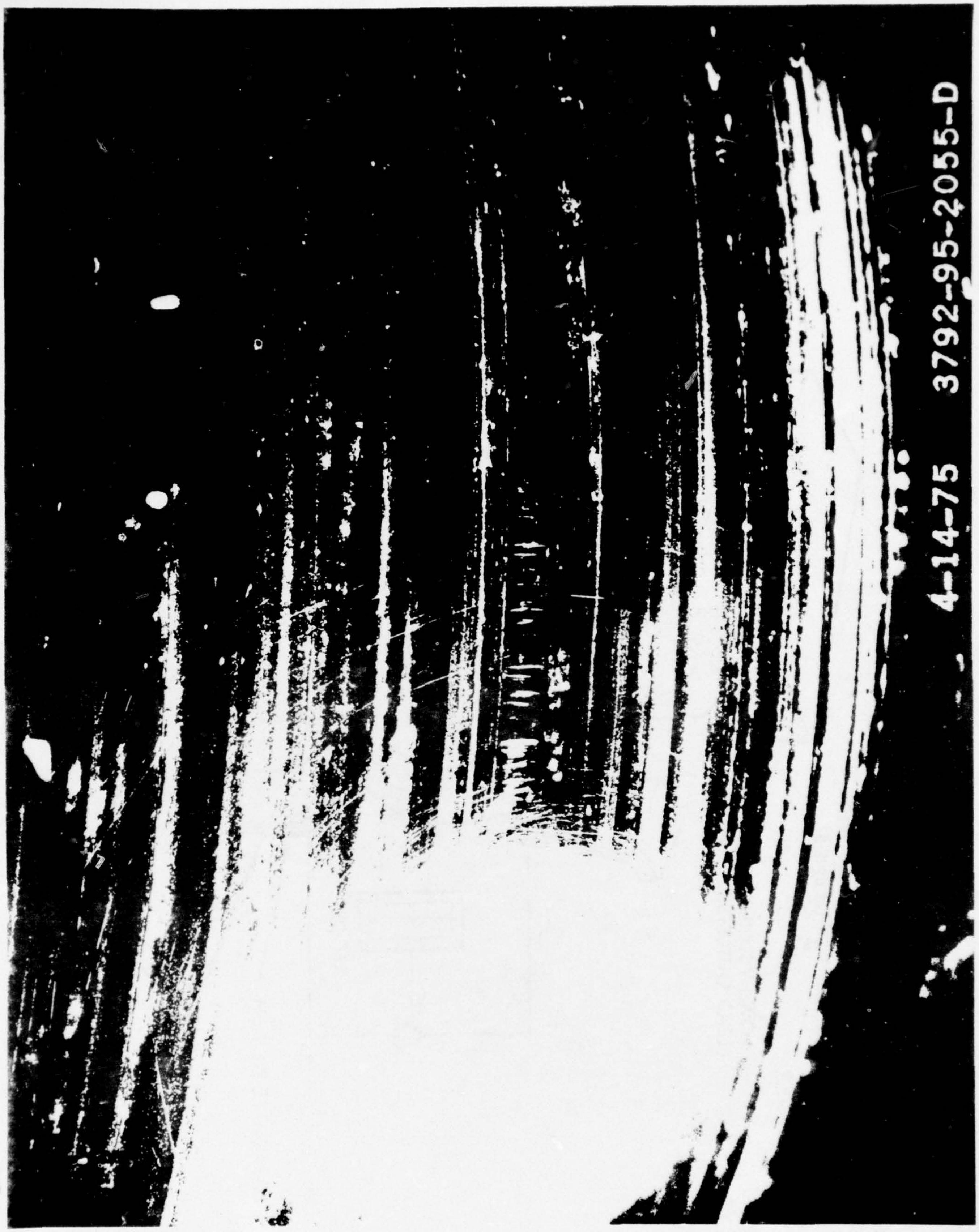
4-14-75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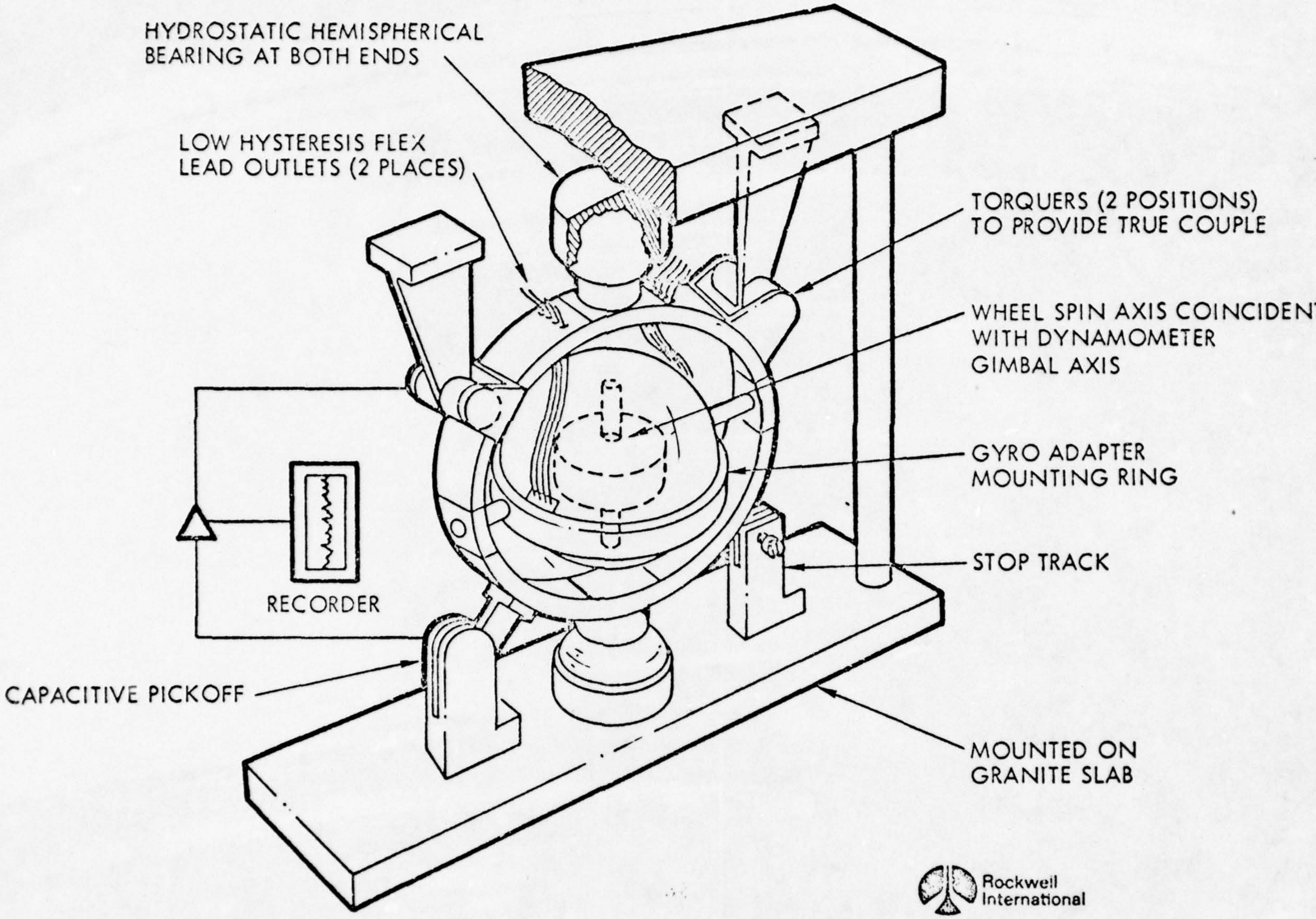
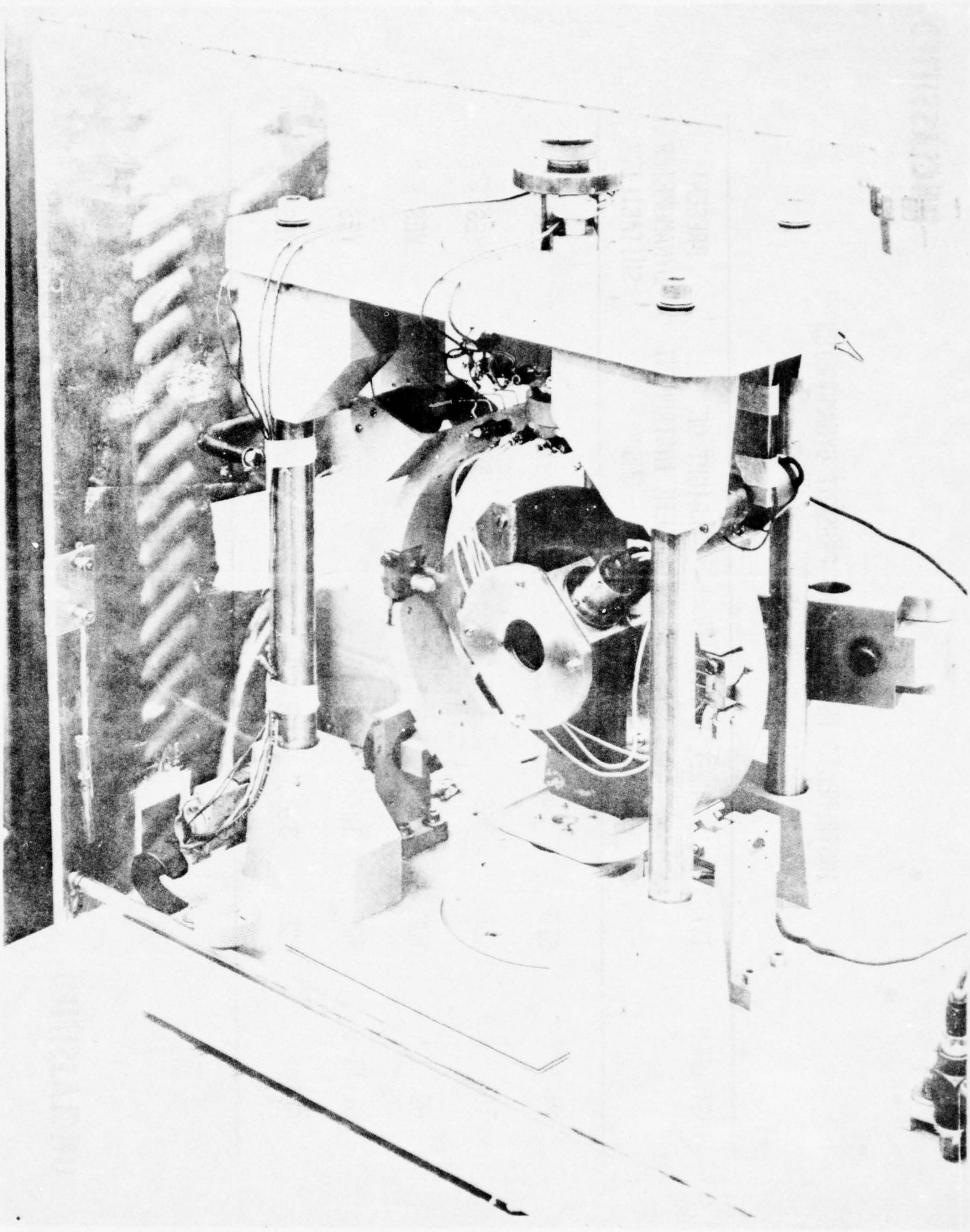
PART-SECTIONAL-FUNCTIONAL VIEW OF DYNAMOMETER





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INSTRUMENTS TESTED USING PRESENT DYNAMOMETER

INSTRUMENT	TYPE	WHEEL DATA		WEIGHT OF COMPLETE INSTRUMENT GMS	PRESENT DYNAMOMETER SUITABILITY
		WT GMS	I $GM\text{-}CM^2$		
PIGA	SDF	4	1.2	816	NO
TGG	SDF	55	149.0	500	YES
G9	TDF	200	1,591.0	1,320	YES
GI-T1-B	SDF	147	732.0	1,612	YES
G6B4	TDF	320	3,672.0	2,209	YES

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SUMMARY

THE DYNAMOMETER PROVIDES A POSITIVE, ACCURATE, AND RAPID MEANS OF DETERMINING QUANTITATIVELY THE CONDITION OF A GAS SPIN BEARING

AS A SCREENING TOOL, IT CAN BE USED TO ASSESS BEARING CONDITION, FROM THE WHEEL ASSEMBLY STAGE THROUGH FINAL ASSEMBLY OF THE INSTRUMENT

AS A DIAGNOSTIC TOOL, IT HAS BECOME AN INTEGRAL PART OF THE PROCEDURE USED TO DEVELOP NEW BEARINGS AND TO EVALUATE SUSPECTED FAULTY BEARINGS

AS A PREDICTIVE TOOL, IT CAN PROVIDE POSITIVE INDICATION ON THE RELIABILITY TO BE EXPECTED FOR A PARTICULAR BEARING

EFFORTS ARE NOW UNDERWAY TO FURTHER EXPLOIT THIS METHOD AND THUS BETTER UNDERSTAND THE PERFORMANCE OF GAS SPIN BEARINGS

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APPLICATION OF A PRECISION TORQUE MEASURING SYSTEM TO MEASURE GYRO SPIN AXIS BEARING CHARACTERISTICS

BY

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HOUSTON, TEXAS 77058

NOVEMBER 1975

OUTLINE

- INTRODUCTION
- PRECISION TORQUE MEASURING SYSTEM (PTMS) DESCRIPTION
- TORQUE TRACE PROFILES AND DEFINITIONS
- TEST VARIABLES
- TORQUE SOURCES
- OVERVIEW OF RESULTS FROM SEVERAL PROGRAMS
- APOLLO 25-IRIG PROGRAM
- 2-DEGREE-OF-FREEDOM GYRO PROGRAM
- GAS-BEARING GYRO PROGRAM
- CLOSING COMMENTS

INTRODUCTION

BACKGROUND

PTMS HAS BEEN USED SINCE 1966 IN INERTIAL COMPONENTS LABORATORY TO EVALUATE OVER 12 GYRO DESIGNS. EXAMPLES OF TEST RESULTS ARE PRESENTED HEREIN.

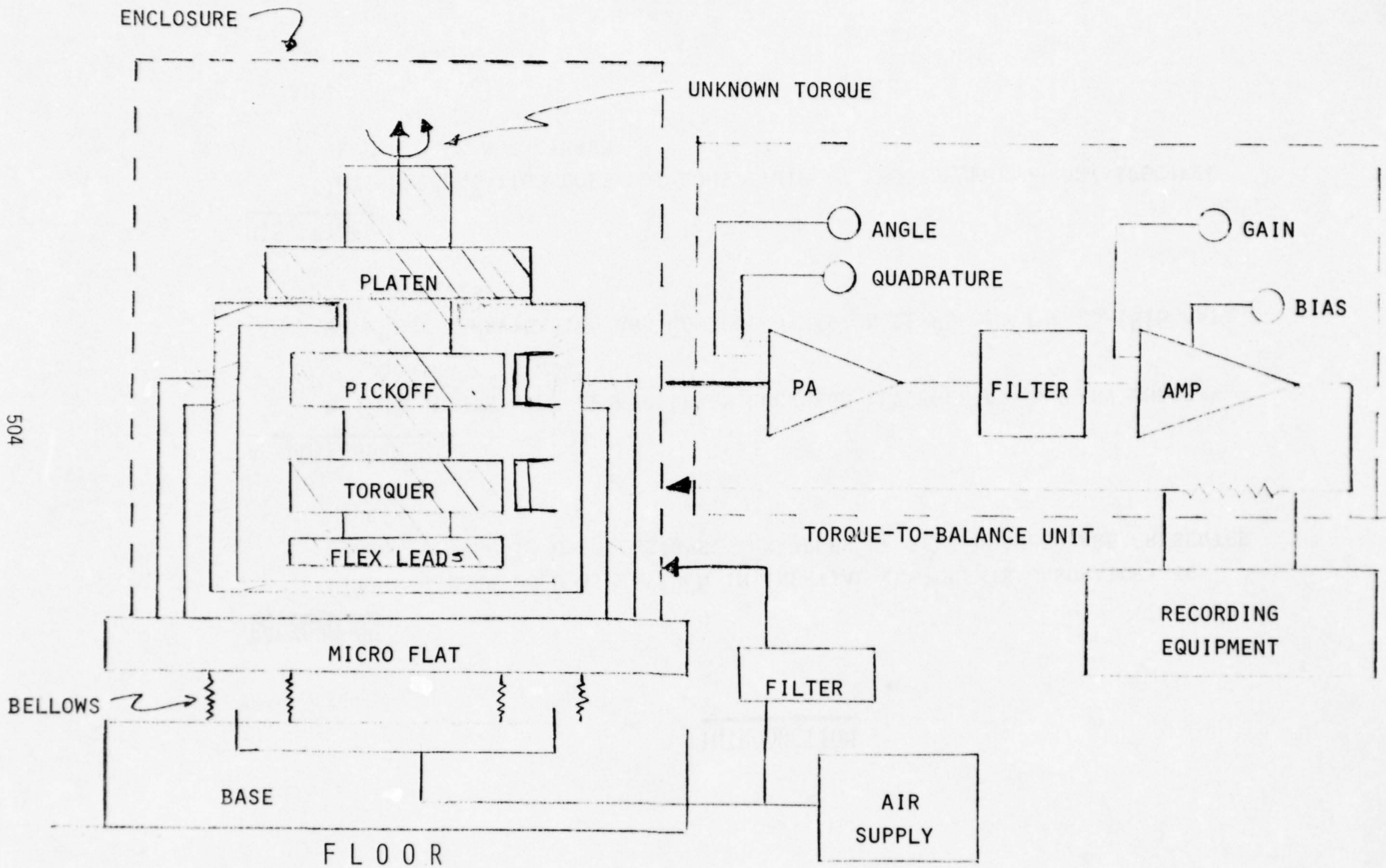
ACKNOWLEDGEMENTS

- JSC TESTS WERE PERFORMED BY LOCKHEED ELECTRONICS COMPANY UNDER CONTRACT TO JSC
- BENDIX NAVIGATION AND CONTROL DIVISION PERFORMED THE 25-IRIG DATA ANALYSIS

DISCLAIMER

THIS PRESENTATION DOES NOT CONSTITUTE AN ENDORSEMENT OF ANY SPECIFIC VENDOR OR MANUFACTURER

PTMS LINE DIAGRAM



PTMS DESCRIPTION

FUNCTION - To provide a continuous, accurate measure of gyro spin motor torques for all modes of wheel operation

MANUFACTURER - Dynamics Research Corporation (DRC), Stonehan, Massachusetts

DESIGNATION - Model TM586, Serial No. 2; one of only three to have been built by DRC.

PRINCIPLE OF OPERATION - The test article is mounted on the PTMS table with the spin axis parallel to the measurement axis of the table. Torques generated about the table axis by the motor assembly of the test article are measured by recording the calibrated closed-loop servo current necessary to maintain the table axis at null.

CAPACITY - Test articles may be gyro motors, gyro floats (gimbals), or completed gyro assemblies.

TORQUE RANGE - 8 full scale ranges from 15 dyne cm to 50,000 dyne cm
(accuracy of 1500 dyne-cm range approximately ±25 dyne cm)

BANDWIDTH - 10 to 15 Hz -- Filters on recording circuits required for ranges below 1500 dyne cm.

PTMS DESCRIPTION

TABLE

- 2 AXIS
  - SENSITIVE AXIS - TORQUE MEASUREMENT AXIS
  - TRUNNION AXIS - POSITIONS PLATEN HOUSING 0 TO 90°
- PLATEN
  - LOW INERTIA
  - GAS BEARING (LOW FRICTION, HIGH STIFFNESS)
  - TEST ARTICLE MOUNTING - SPIN AXIS PARALLEL TO SENSITIVE AXIS
  - CONNECTED TO
    - PICKOFF
    - TORQUER
    - FLEX LEAD ASSEMBLY (TEST ARTICLE ELECTRICAL SERVICE)
  - ANGULAR FREEDOM ±0.5 DEGREES
- TABLE ENCLOSURE - MINIMIZE AIRBORNE DISTURBANCES
- TABLE SUPPORT - GRANITE SLAB
  - BARRY SERVA-LEVEL-VIBRATION ISOLATION SYSTEM
- AIR SUPPLY - FACILITY AIR HIGHLY FILTERED, DRY

PTMS DESCRIPTION

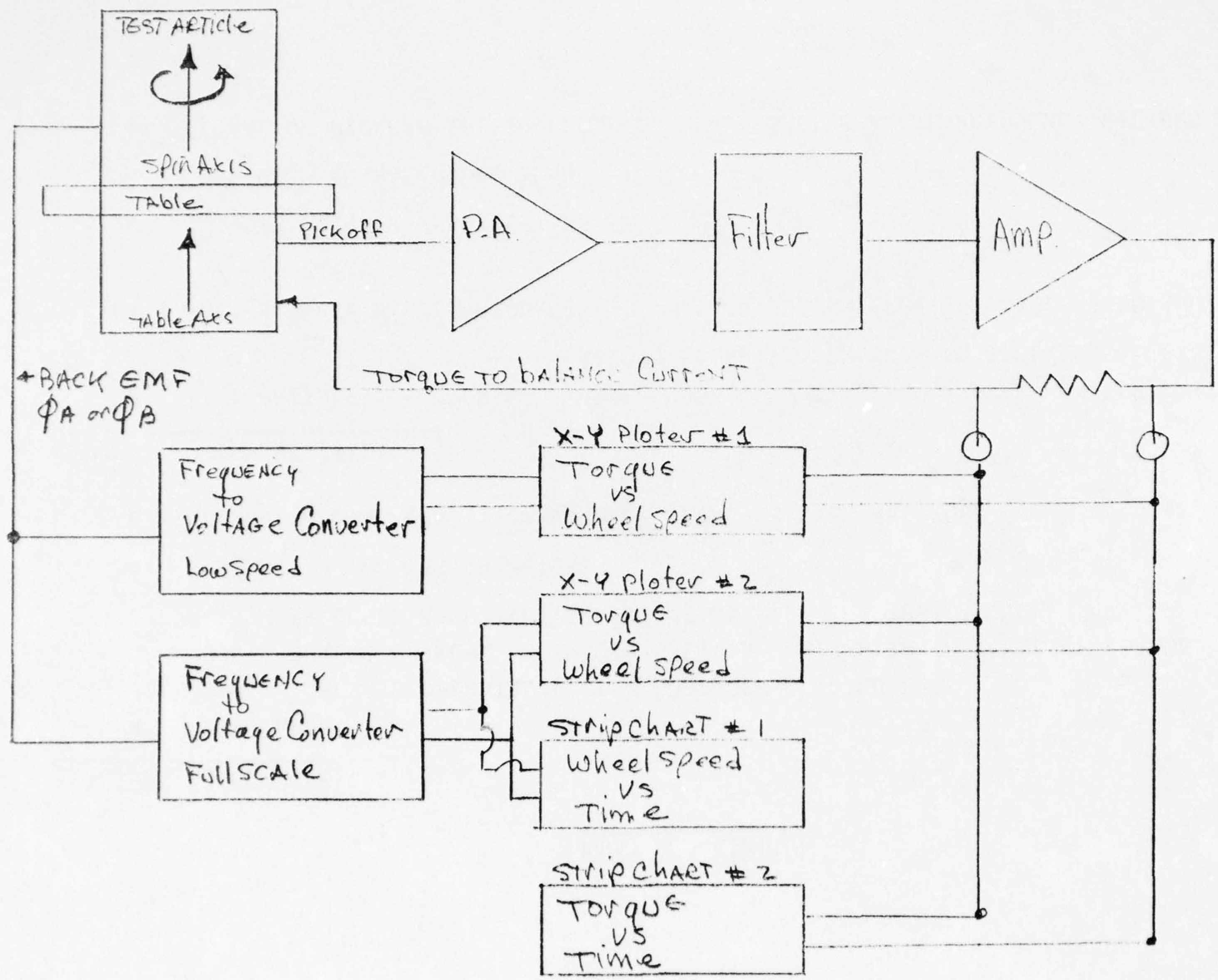
ELECTRONICS CONSOLE

- SERVO LOOP
  - TABLE IS OPERATED CLOSED-LOOP SERVO TO NULL
  - ANALOG CURRENT TO THE TORQUER IS CALIBRATED IN TERMS OF TORQUE PRODUCED ABOUT THE SENSITIVE AXIS BY THE TEST ARTICLE
- DISPLAYS - TWO WESTON METERS
- RECORDING EQUIPMENT - SANBORN 320 DUAL-CHANNEL RECORDER

SUPPORT EQUIPMENT (TYPICAL)

- TEST ARTICLE ELECTRONICS - WHEEL SUPPLY, VOLTAGE AND POWER MONITOR UNIT (SERVO LOOP, TEMPERATURE CONTROLLER, SG EXCITATION)
- ANADEX MODEL PI408 FREQUENCY-TO-VOLTAGE CONVERTERS (10 RANGES FROM 100 Hz TO 52.8 Hz)
- HP5451B FOURIER ANALYZER SYSTEM
- MOSELEY AUTOGRAF MODEL 2FRA X-Y RECORDER
- VIBRATION PICKUPS (PIEZOELECTRIC ACCELEROMETERS) AND FREQUENCY FILTERS

PTMS TEST Configuration



OVERVIEW

PTMS UNIQUE CAPABILITY

THE PTMS OUTPUT IS A CONTINUOUS DISPLAY OF THE NET SUM OF TORQUES AND TORQUE DISTURBANCE OVER THE COMPLETE RANGE OF WHEEL ROTATION SPEEDS. THE TORQUES ARE PRODUCED BY THE MOTOR, THE WHEEL, BEARING FRICTION FORCES (CAUSED BY LUBRICATION, GEOMETRY, AND PRELOAD), BALL DYNAMICS, AND RETAINER DYNAMICS. THE OUTPUT SCALING MAY BE SELECTED OR CHANGED DURING THE TEST WITHOUT AFFECTING THE RESULTS.

PTMS APPLICATIONS

PRIMARY - EVALUATION OF GYRO SPIN AXIS BEARINGS
SECONDARY - EVALUATION OF GYRO SPIN MOTOR DESIGN PARAMETERS

BEARING EVALUATION

RUNUP, RUNNING, AND RUNDOWN TORQUES ARE DISPLAYED AS A FUNCTION OF TIME. RUNDOWN VS. WHEEL SPEED TORQUE TRACES APPEARS TO BE THE MOST INFORMATIVE AS THE WHOLE ROTATIONAL SPEED SPECTRUM IS COVERED, AND WHEEL HUNT IS ABSENT. TRACE PARAMETERS HAVE NOT BEEN CORRELATED ON A 1-TO-1 BASIS WITH SPECIFIC BEARING DEFECTS; HOWEVER, THEY ARE CAUSED BY THE SUM OF (1) THE PHYSICAL CONDITION OF THE SPIN AXIS BEARINGS (LUBRICATION QUANTITY AND QUALITY, GEOMETRY, AND SURFACE FINISH), (2) ROTATIONAL STABILITY OF THE RETAINER AND BALLS, AND (3) HUNT OSCILLATION AMPLITUDE AND FREQUENCY DURING SYNCHRONOUS ROTATION.

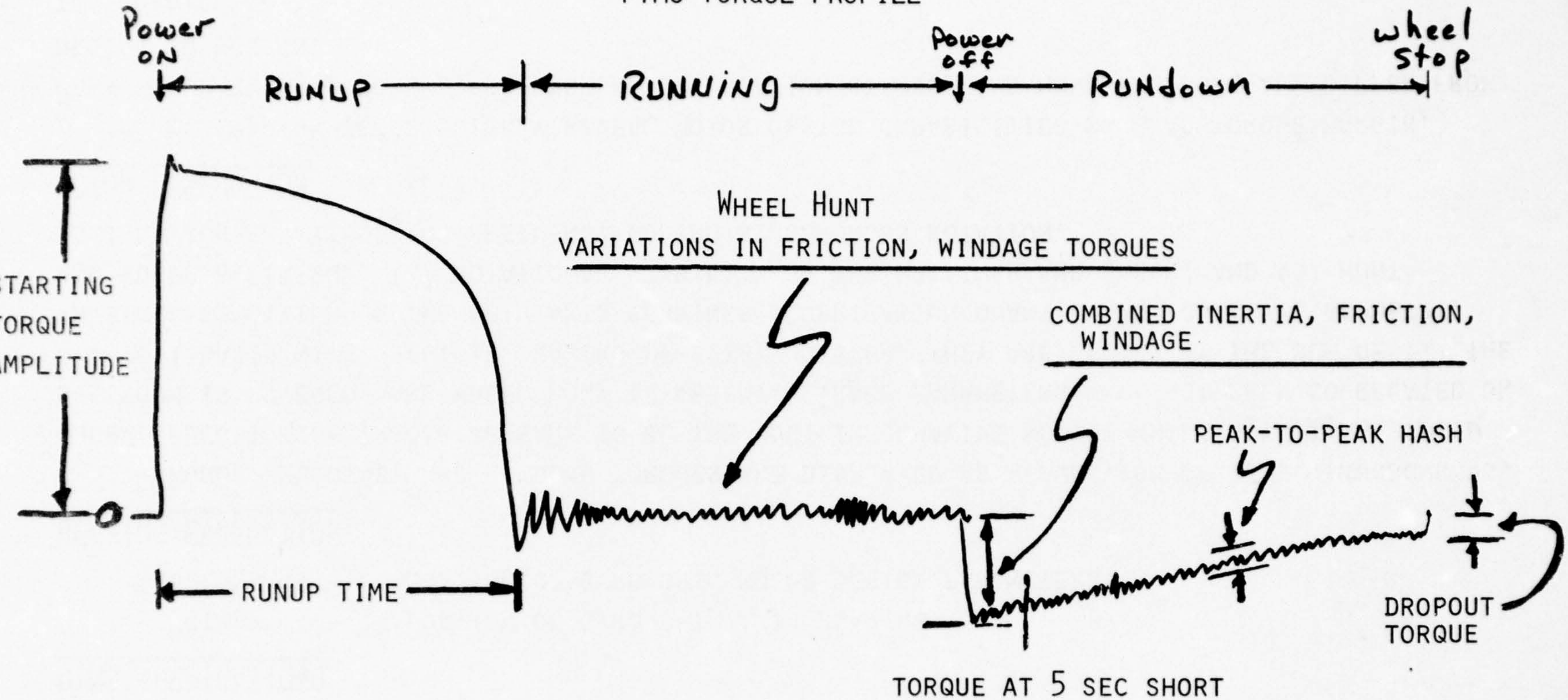
MOTOR EVALUATION

EVALUATION TESTS QUICKLY REVEAL MOTOR DESIGN CAPABILITIES SUCH AS TORQUE MARGIN. PEAK RUNUP TORQUE, TORQUE RESPONSE AFTER ROTATION STARTS, AND RUNDOWN SLOPE ALL DIFFER FROM DESIGN TO DESIGN.

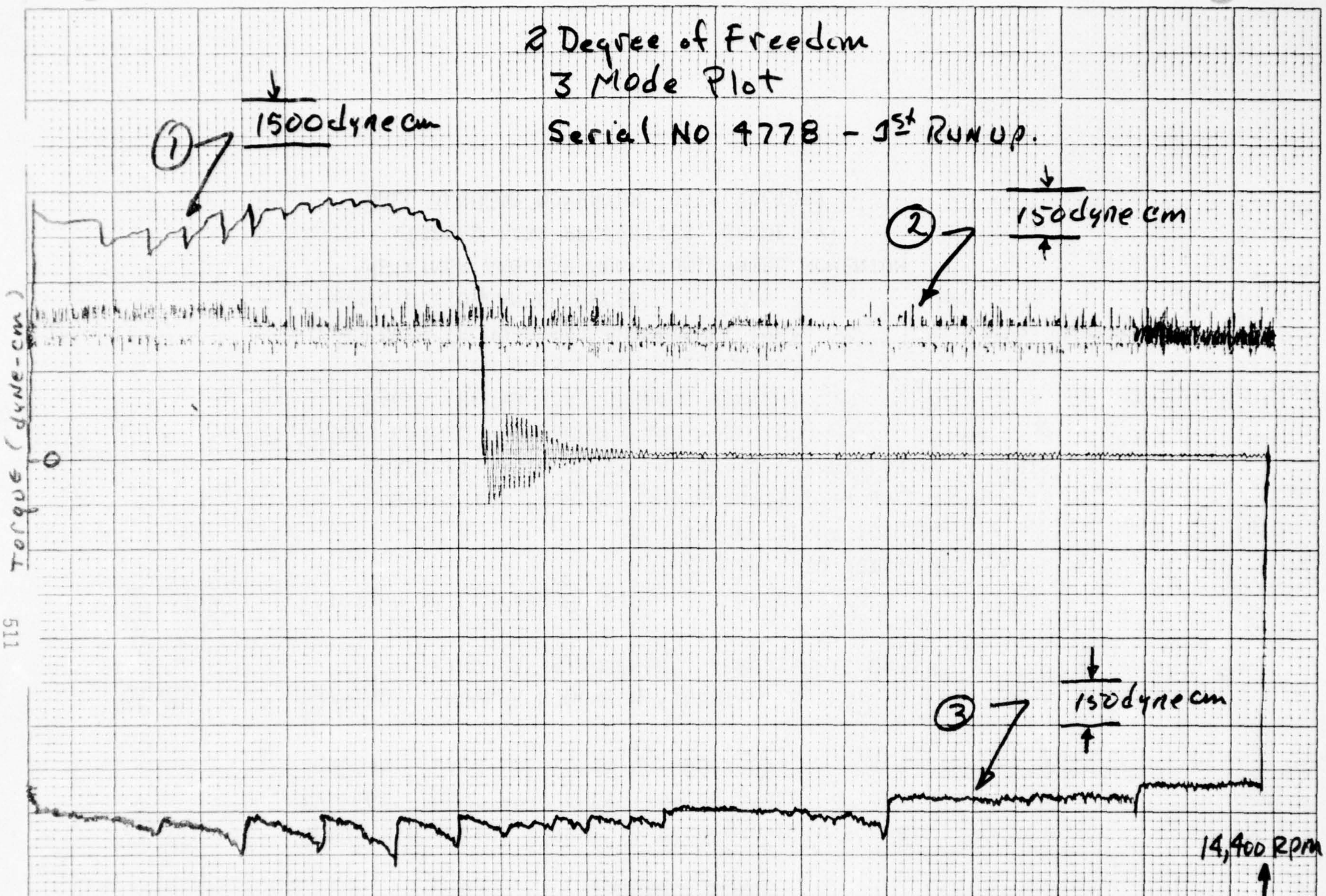
TEST VARIABLES

WHEEL SUPPLY VOLTAGE, FREQUENCY, PHASE; SPIN AXIS ORIENTATION WRT GRAVITY; TEST ARTICLE TEMPERATURE, AND OPERATING HISTORY.

PTMS TORQUE PROFILE



$$\text{TORQUE MARGIN} = \frac{\text{STARTING TORQUE AMPLITUDE}}{\text{TORQUE AT POWER OFF}} \qquad \text{TORQUE} = \frac{H}{W}\alpha_{SP}$$



① - RUN UP - TORQUE VS TIME
② - RUNNING - EXPANDED TORQUE SCALE, SLOWER TRACE SPEED
③ - RUNDOWN - TORQUE VS RPM (WHEEL SPEED).

TORQUE SOURCES

MOTOR - Runup - starting torque (electromagnetic force)
Running - hunt frequency (torque angle)
Rundown - back EMF (open or shorted)

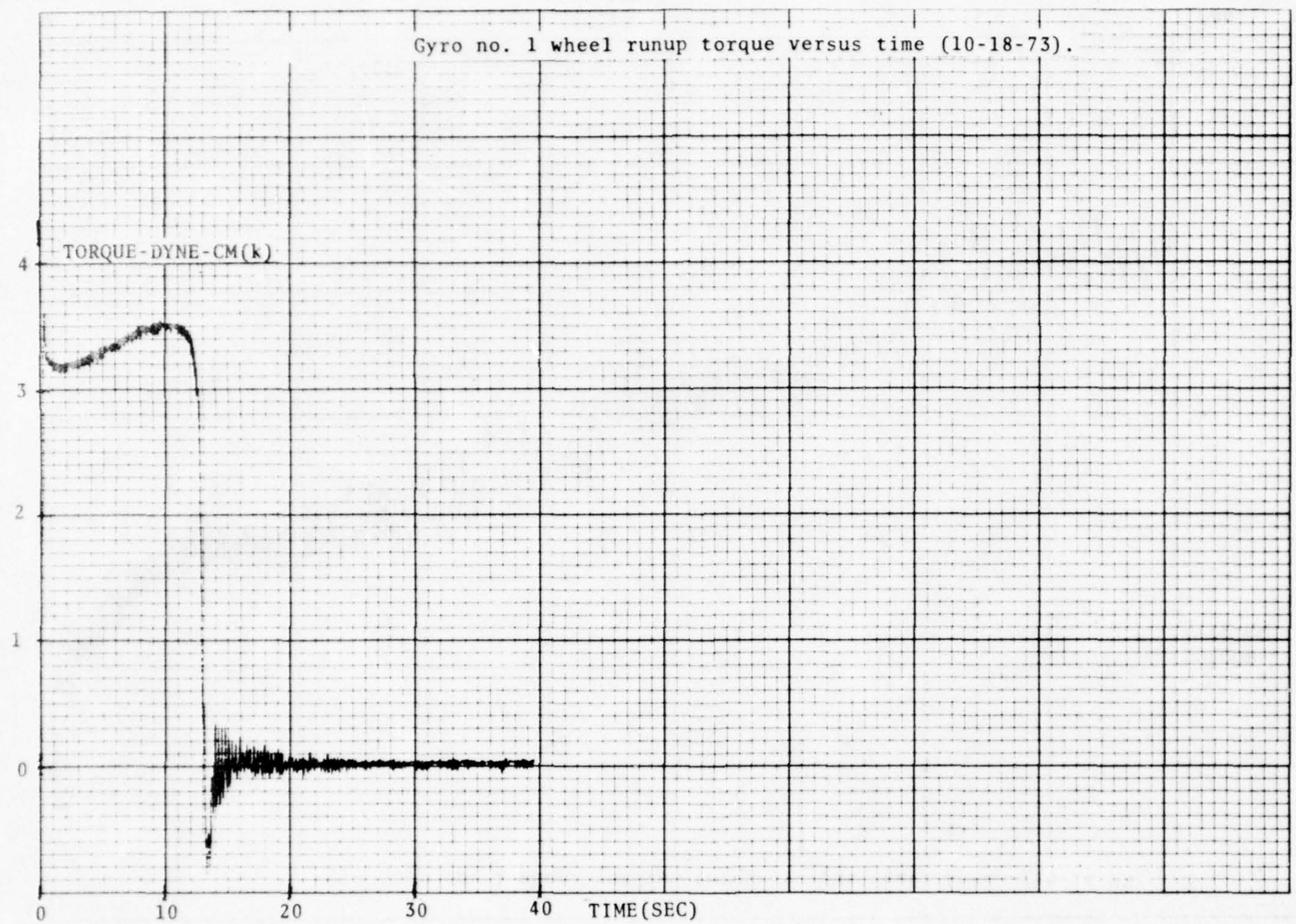
WHEEL - Running - angular momentum (inertia, speed)
- windage (atmosphere, aerodynamic drag)

BEARINGS - Friction at Contact Points:
1. Ball to Race
2. Ball to Retainer
3. Retainer to Land

Lubrication (quality and quantity) in ball path
Lubrication (quality and quantity) at contact points

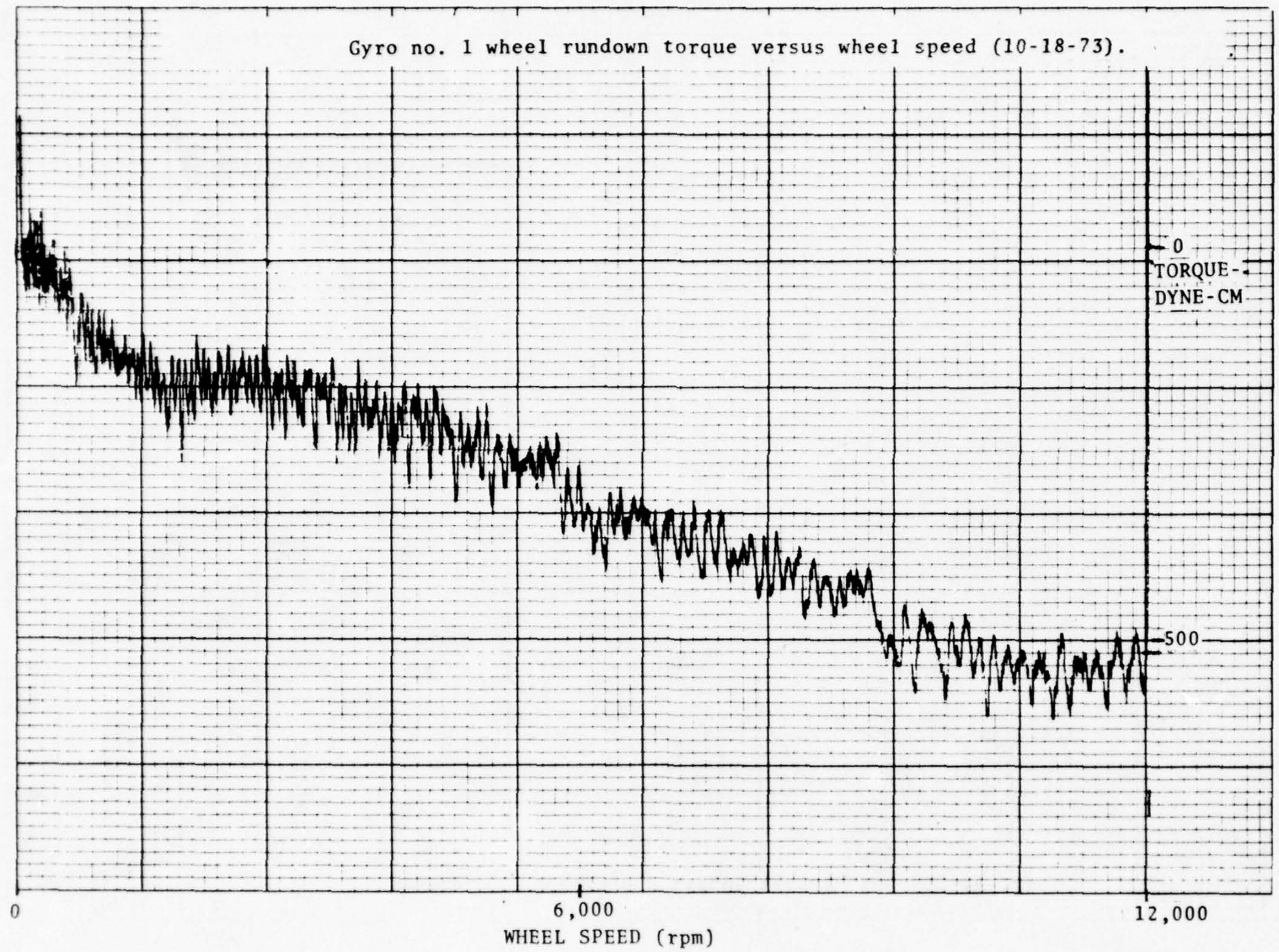
- Forces Caused by Geometry and Preload
  Balls (roundness, surface finish)
  Races (roundness, surface finish)
  Lands (roundness, surface finish)
- Dynamic Disturbance Forces
  Retainer angular momentum, whirl momentum
  (speed mass properties, geometry)
  Ball angular momentum (spin vector)

Example 1

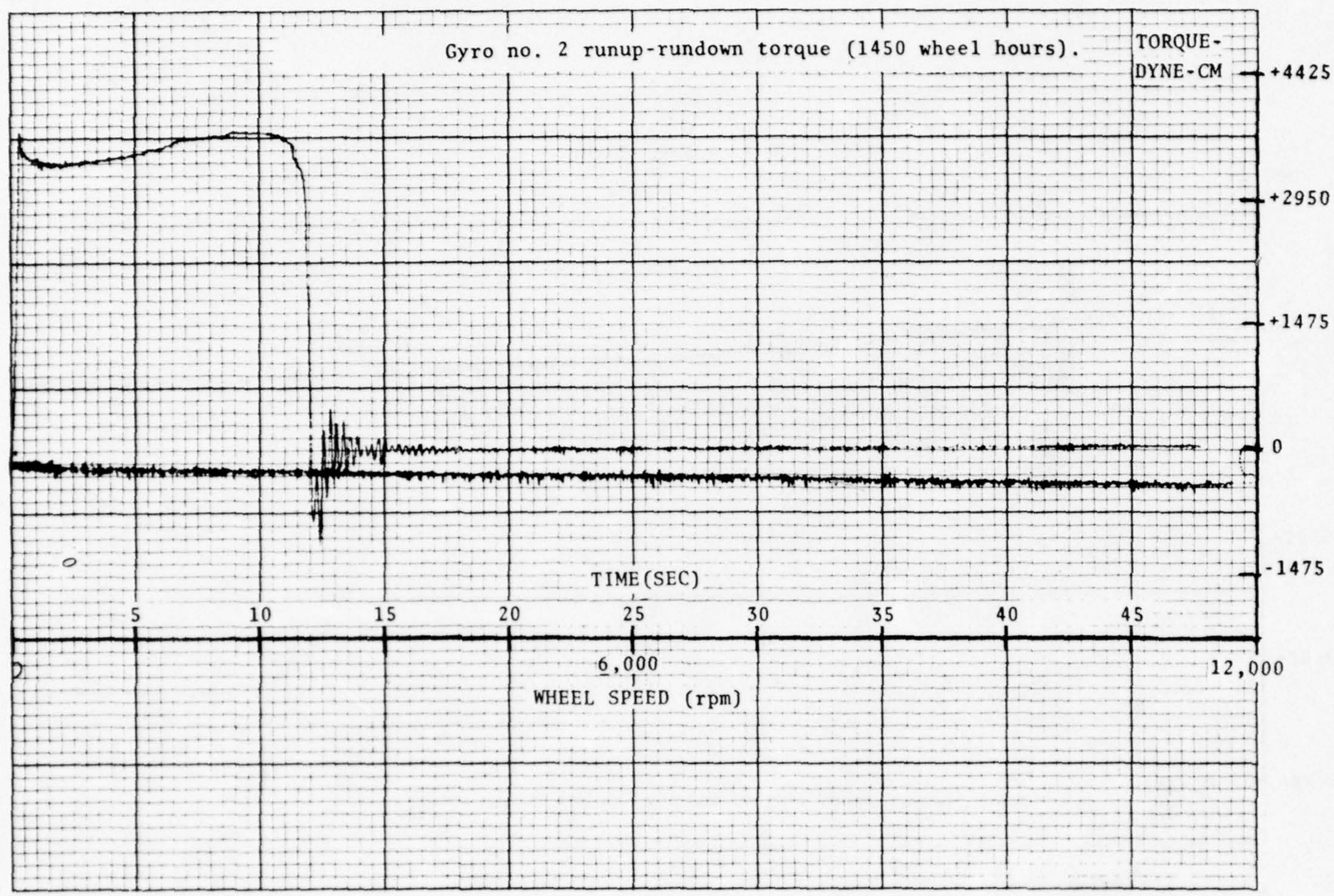


Gyro no. 1 wheel runup torque versus time (10-18-73).

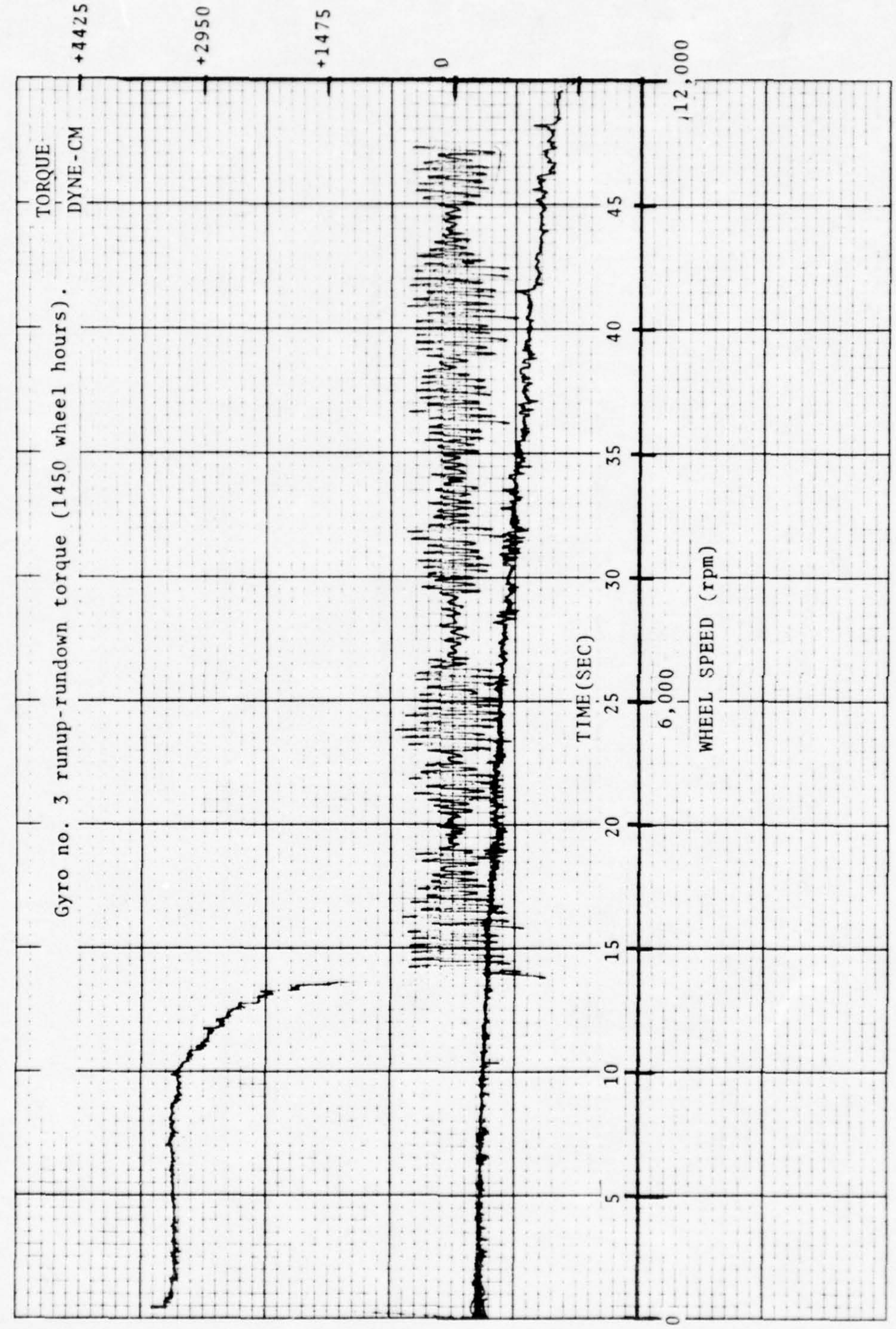
Example 2


Gyro no. 1 wheel rundown torque versus wheel speed (10-18-73).
0
TORQUE-
DYNE-CM
500
0
6,000
12,000
WHEEL SPEED (rpm)

Example 3

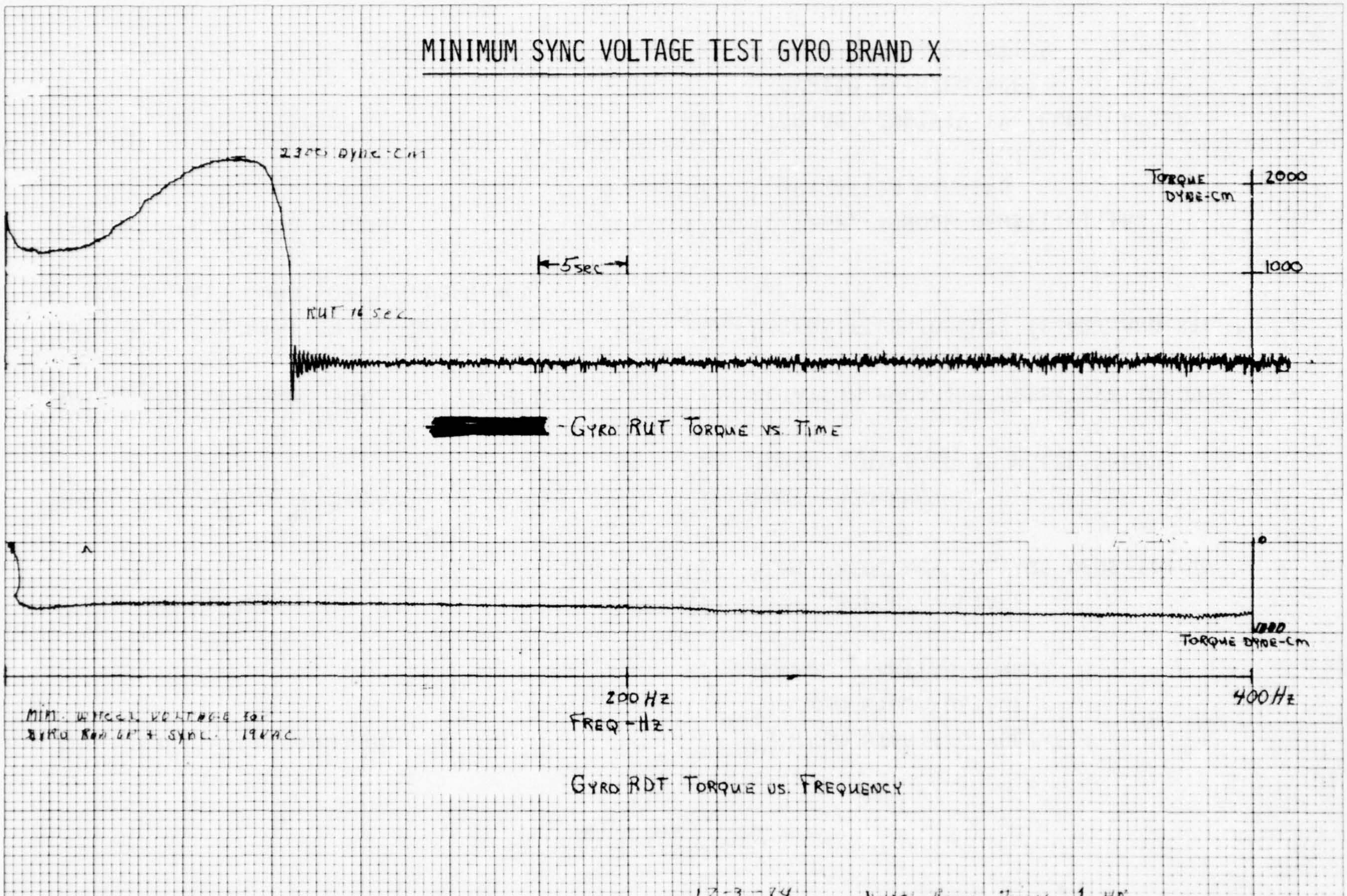

Gyro no. 2 runup-rundown torque (1450 wheel hours).
TORQUE-
DYNE-CM
+4425
+2950
+1475
0
-1475
TIME (SEC)
5
10
15
20
25
30
35
40
45
6,000
12,000
WHEEL SPEED (rpm)

Example 4



Gyro no. 3 runup-rundown torque (1450 wheel hours).

Example 5


MINIMUM SYNC VOLTAGE TEST GYRO BRAND X
TORQUE DYNE-CM
2000
1000
5 SEC
GYRO RUT TORQUE VS. TIME
TORQUE DYNE-CM
200 Hz
400 Hz
FREQ - Hz
GYRO RDT TORQUE VS. FREQUENCY

TEST VARIABLES

Wheel Excitation Voltage	(1) Minimum starting voltage (2) Minimum sync voltage (3) Normal starting torque
Operating Voltage	(1) Sync dropout voltage (2) Hunt frequency voltage sensitivity
Wheel Excitation Frequency	(1) Hunt frequency (2) Torques related to wheel speed
Wheel Voltage Phase (Ball Bearings Only)	(1) Rotation polarity sensitive torques
Spin Axis Orientation WRT Gravity (Especially Good for Gas Bearings)	(1) G-sensitive torques (start and stop)
Test Article Temperature	(1) Voltage, torque sensitivities (2) Lubrication margins
Past Operating History	(1) Storage sensitivity (lubrication system maintenance) (2) Warmup characteristics

APOLLO 25 IRIG

TEST PROGRAM

- Apollo 25 IRIG's - Quantity 25 with R-2 size ball bearings
- Operated several thousand hours past rejection for ADDA instability
- JSC Tests - Servo drift, bearing frequency analysis, PTMS tests
- Teardown Analysis - Bendix Navigation and Control Division
  See Bendix TR1864, "Final Report, Apollo Gyro Bearing Analysis Program," (NAS 9-8436) dated March 18, 1970, by A. Carriero and D. Schauffler for a complete description of the program and all results.

DATA ANALYSIS

- PTMS traces consisted of:
  (1) Torque vs. Time (runup, running, rundown)
  (2) Torque vs. RPM (full range RPM)
  (3) Torque vs. RPM (expanded scale 1700 RPM to zero)
- PTMS trace records were reduced to 25 parameters.
- 8 parameters were then selected for correlation with teardown findings:
  (1) Peak-to-peak hash (dyne cm) - high frequency oscillations during rundown
  (2) Hash duration (RPM) - duration of highest hash level
  (3) Dropout torque (dyne cm) - torque level before high rate drop to zero
  (4) Torque at 5 sec short (dyne cm) - wheel short 5 sec after power removed
  (5) Initial torque amplitude (dyne cm) - peak motor torque
  (6) Average trace width (dyne cm) - peak-to-peak torque on low speed plot (below 1700 RPM)
  (7) Runup time (sec) - time to sync
  (8) Rundown time (sec) - time to stop

APOLLO 25-IRIG PROGRAM

CONCLUSIONS

- 6 TRACE PARAMETERS CORRELATED WITH 2 GYRO DRIFT STABILITY PARAMETERS AND WITH 10 SPIN AXIS BEARING PROPERTIES
- PTMS TRACE CHARACTERISTICS WHEN PROPERLY UTILIZED CAN BE EFFECTIVELY UTILIZED TO EVALUATE THE CONDITION OF MOST GYRO MOTOR WHEELS

APPLYING 2-SIGMA LIMITS RESULT IN THE FOLLOWING:

(1) PROBABILITY OF REJECTING A GOOD UNIT - LESS THAN 2.5%

(2) PROBABILITY OF ACCEPTING A BAD UNIT -

LESS THAN 16% ON THE BASIS OF PEAK-TO-PEAK HASH ONLY

LESS THAN 4.5% ON THE BASIS OF HASH DURATION ONLY

LESS THAN 25% ON THE BASIS OF AVERAGE LOW SPEED TRACE WIDTH ONLY

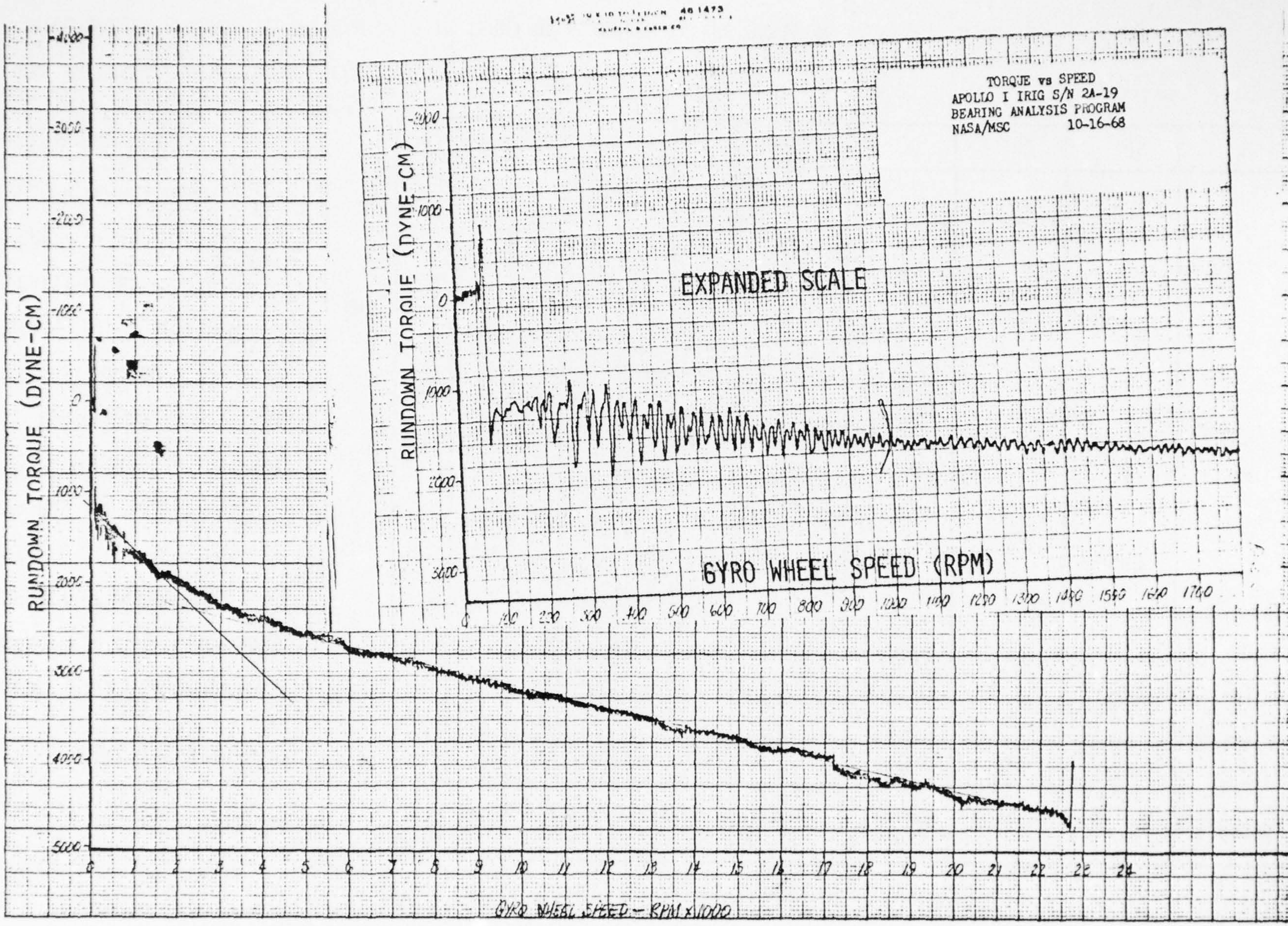
25 IRIG PROGRAM

SIGNIFICANT CORRELATION TEST RESULTS

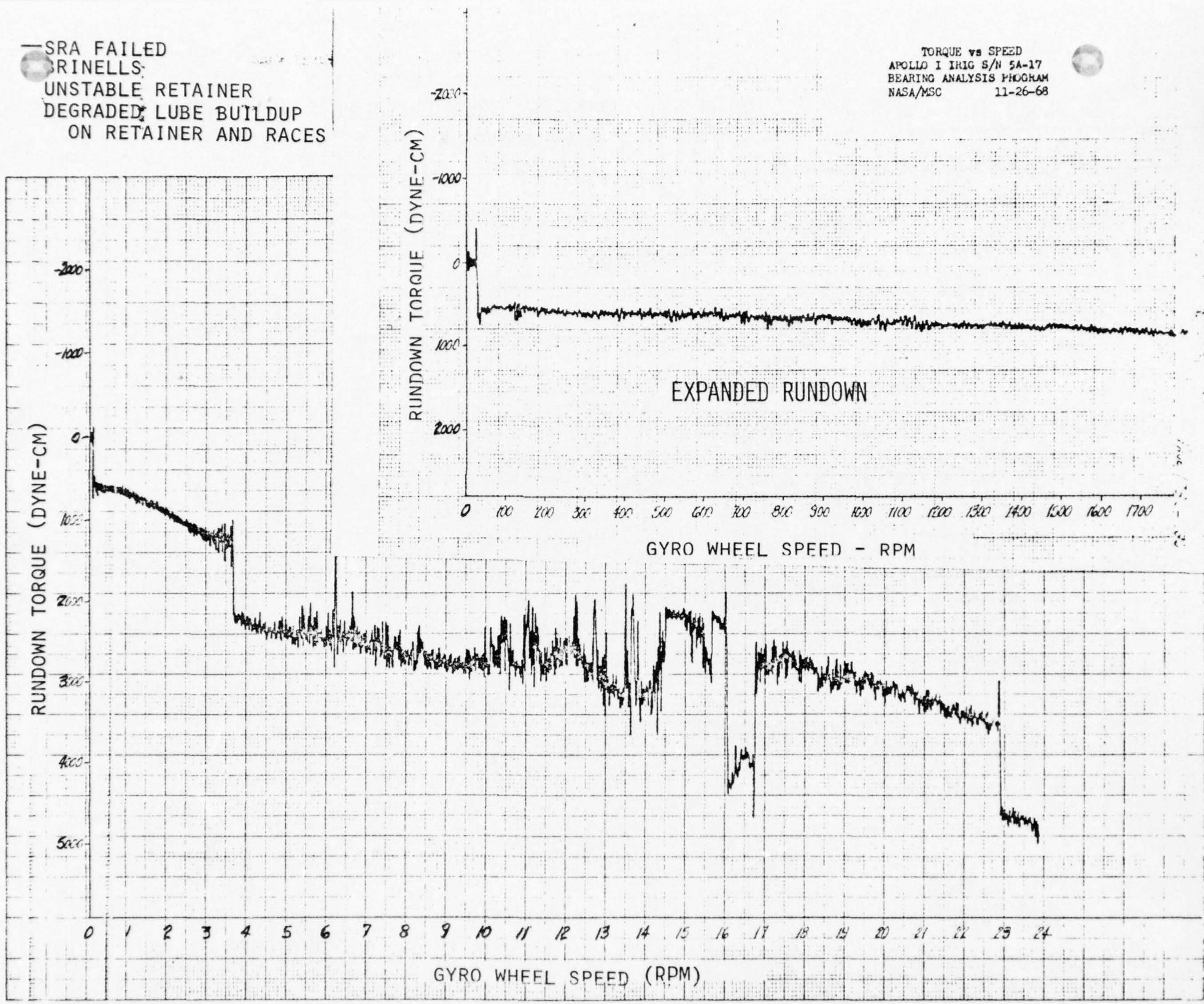
PTMS TRACES	Peak-to-Peak Hash		Hash Duration		AVG Trace Width		5-sec Short Torque		Dropout Torque	Initial Torque	Runup Time	Rundown Time
BEARING QUALITY/DEFECTS	Raw	Rated	Raw	Rated	Raw	Rated	Raw	Rated	Rated	Raw		
1. SURFACE FINISH - OUTER RACE	.41	-	.44	.50	.42	-					.48	.39
2. SURFACE FINISH - INNER RACE							.46	.50	.41	.42		
3. SEVERITY OF OUTER RACE	.54	.45			.50	.39						
4. RESIDUAL OIL - BEARINGS		.38			.40	.35					.32	
5. RETAINER INSTABILITY		.50	.74	.85				.35				
6. GYRO PERFORMANCE - Δ10 (ADIA)								.32	.34		.47	.44
7. GYRO PERFORMANCE - Δ25 (ADIA)								.40	.37		.52	
8. BRINELLS (RATED)	.35				.38	.34						
9. RESIDUAL OIL - RETAINERS		.44	.38	.44								
10. SEVERITY OF BALLS					.35	43						
11. SEVERITY OF INNER RACE			.41	.46								
12. RETAINER POCKET WEAR				.34								
AVERAGE VALUES	.43	.44	.49	.52	.41	.38	.46	.39	.37	.42	.45	.42

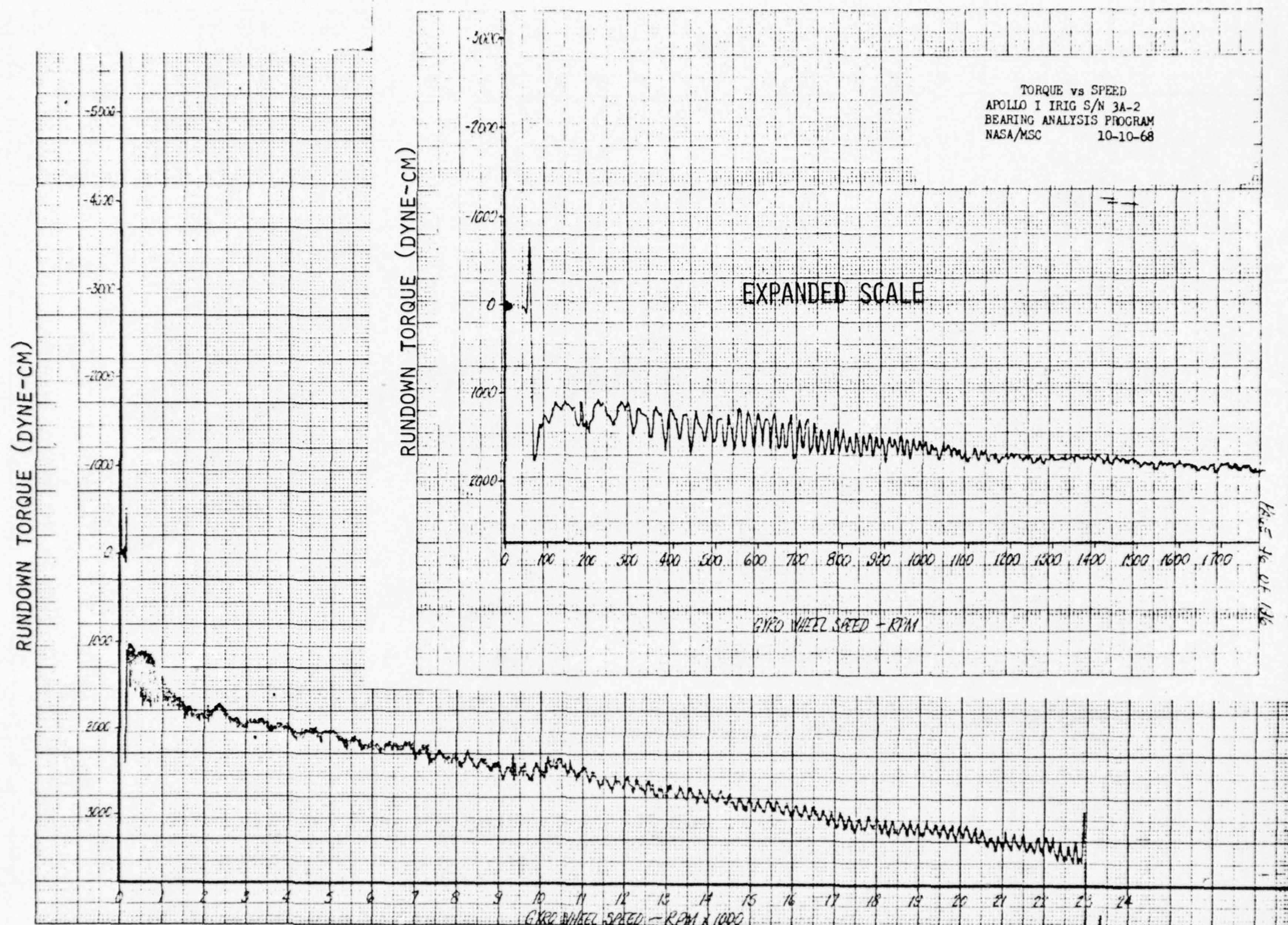
RAW VALUES ARE DIRECT NUMERICAL COMPARISONS.

RATED VALUES CATEGORIZE THE RAW DATA IN TERMS OF SEVERITY ON THE BASIS OF VALUES 1 TO 10.



BRINELLS, LUBRICANT DEGRADATION (SEVERE); MODERATE RETAINER INSTABILITY


SRA FAILED
BRINELLS
UNSTABLE RETAINER
DEGRADED LUBE BUILDUP
ON RETAINER AND RACES
TORQUE vs SPEED
APOLLO I IRIG S/N 5A-17
BEARING ANALYSIS PROGRAM
NASA/MSC 11-26-68
EXPANDED RUNDOWN
RUNDOWN TORQUE (DYNE-CM)
GYRO WHEEL SPEED - RPM
RUNDOWN TORQUE (DYNE-CM)
GYRO WHEEL SPEED (RPM)



MINUS SIDE - DISCOLORED BALLTRACK, MULTIPLE BALL BRINELLS, BALLS HAD CUTS AND FLATS

2-DEGREE-OF-FREEDOM GYRO

TEST OBJECTIVE

OBTAIN BASELINE TEST RESULTS ON GYROS

TEST ARTICLES

QUANTITY - 8

CONFIGURATION - DRY, FLEX JOINT, SUSPENDED FREE ROTOR GYRO
- ROTATING FLEXURE IS ON OPPOSITE END OF SHAFT FROM SYNCHRONOUS HYSTERESIS MOTOR

TEST CONFIGURATION

- GYROS MOUNTED WITH SPIN AXIS PARALLEL TO TABLE AXIS
- GYROS PREVIOUSLY STORED AT ROOM TEMPERATURE FOR ~6 MONTHS
- GYROS TESTED OPEN-LOOP AT ROOM TEMPERATURE
- RUNUP, 15 MINUTES RUN, RUNDOWN - REPEATED 2 OR 3 TIMES

TEST RESULTS

- INITIAL RUNUP GENERALLY ERRATIC AND NOT CHARACTERISTIC OF SUBSEQUENT RUNUPS
- RUNNING AND RUNDOWN TORQUES WERE NOT CONSISTENT
- ON RUNDOWN VS. RPM PLOTS BELOW 1000 RPM, TORQUE AND RPM BOTH APPEAR TO BE ERRATIC

2-DEGREE-OF-FREEDOM GYRO

(CONTINUED)

CONCLUSIONS

(1) INITIAL RUNUP IS A GOOD INDICATOR OF HOW WELL THE LUBRICATION SYSTEM IS MAINTAINED DURING STORAGE

(2) VARIATION OF RESULTS INDICATES A LARGE VARIATION IN THE SPIN AXIS BEARINGS WHEREAS DRIFT STABILITY DID NOT

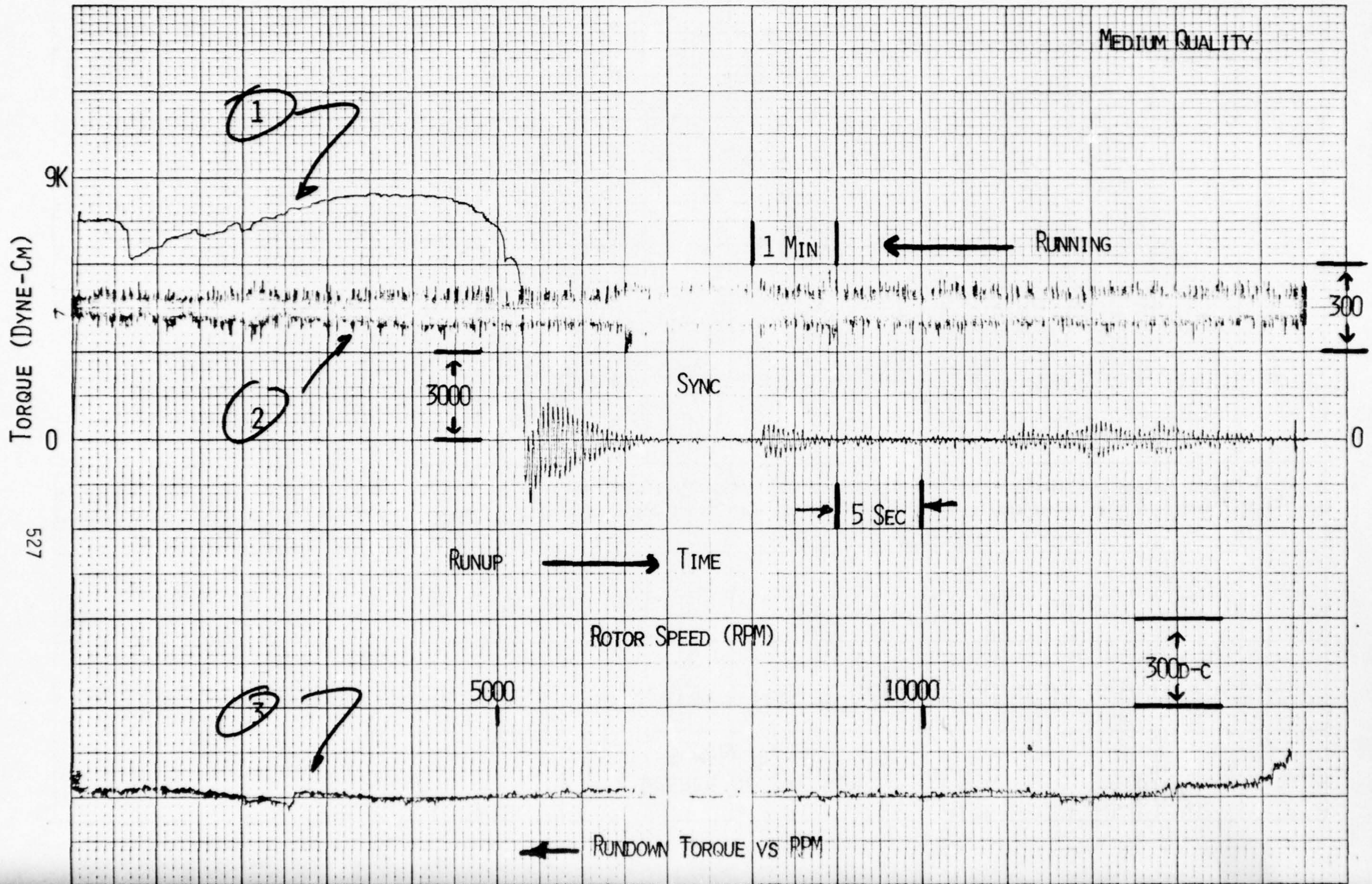
(3) OSCILLATION INSTABILITY OF TORQUE VS. RPM AT LOW SPEEDS (1000 RPM TO ZERO) IS CAUSED BY WHEEL OSCILLATIONS ABOUT AN AXIS

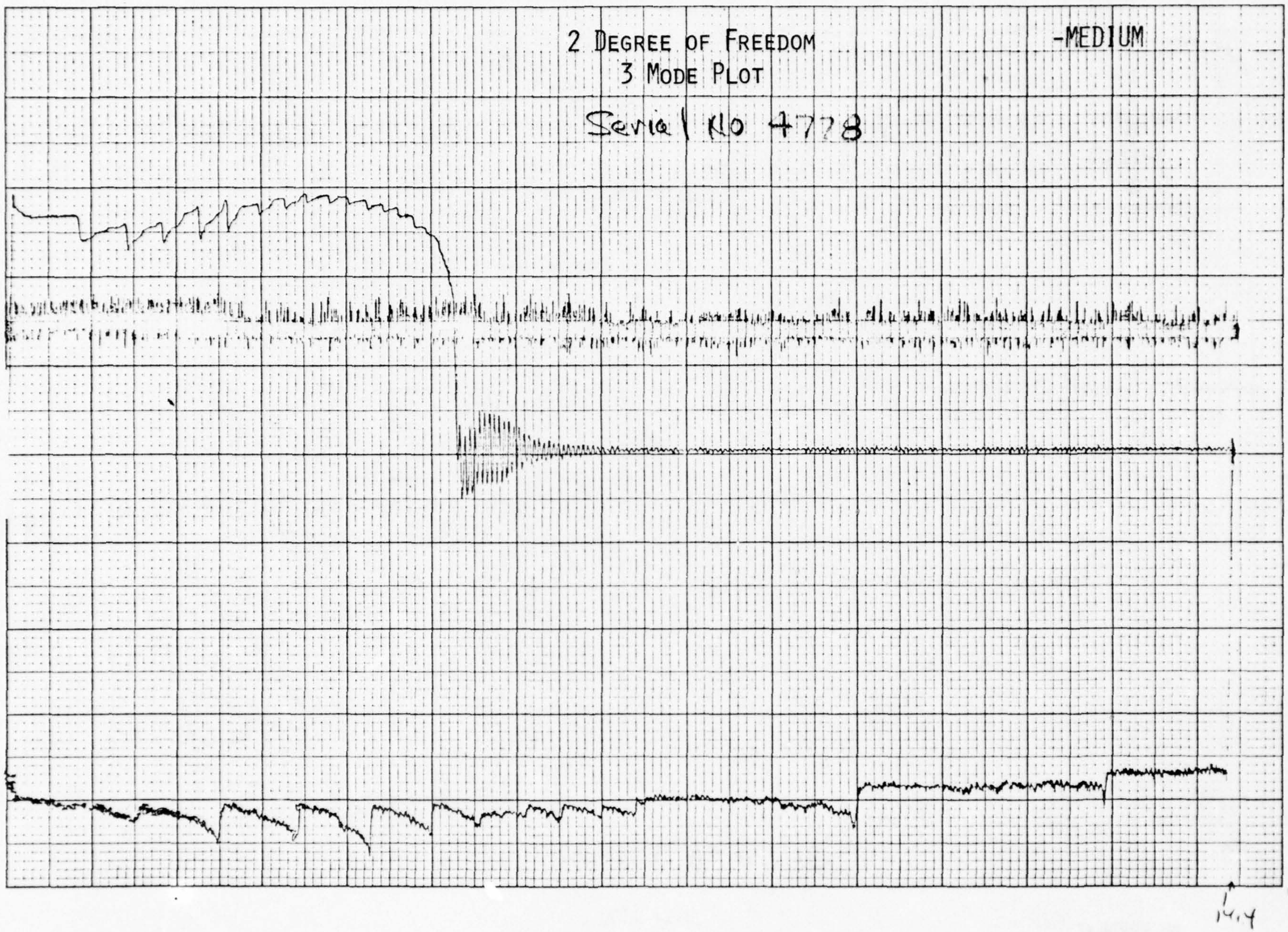
(4) RUNDOWN TORQUE TRACES BELOW 1000 RPM VS. TIME PRODUCE RESULTS WHICH ARE EASIER TO ANALYZE.

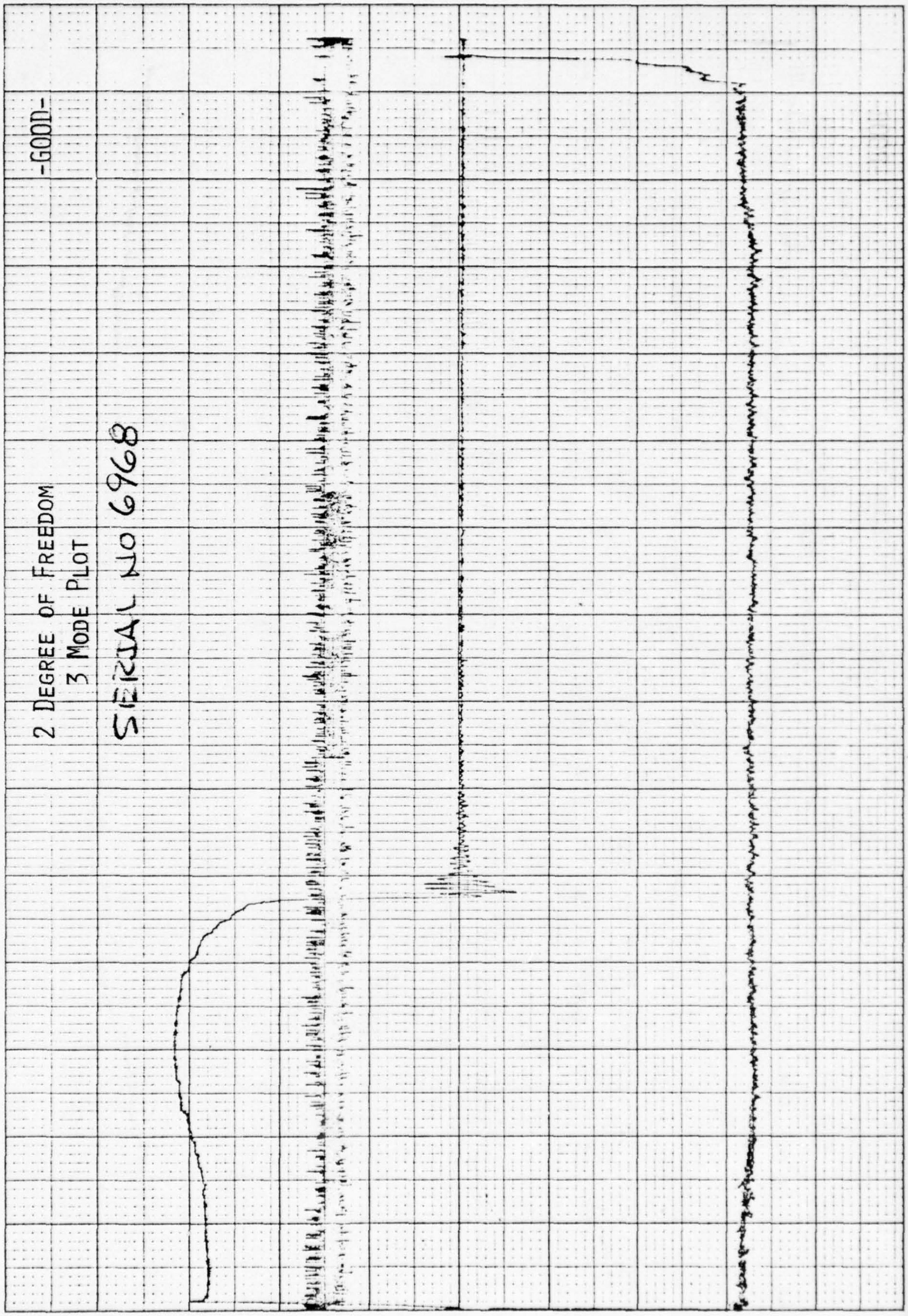
1 RUNUP AND RUN
2 EXPANDED RUN
3 RUNDOWN

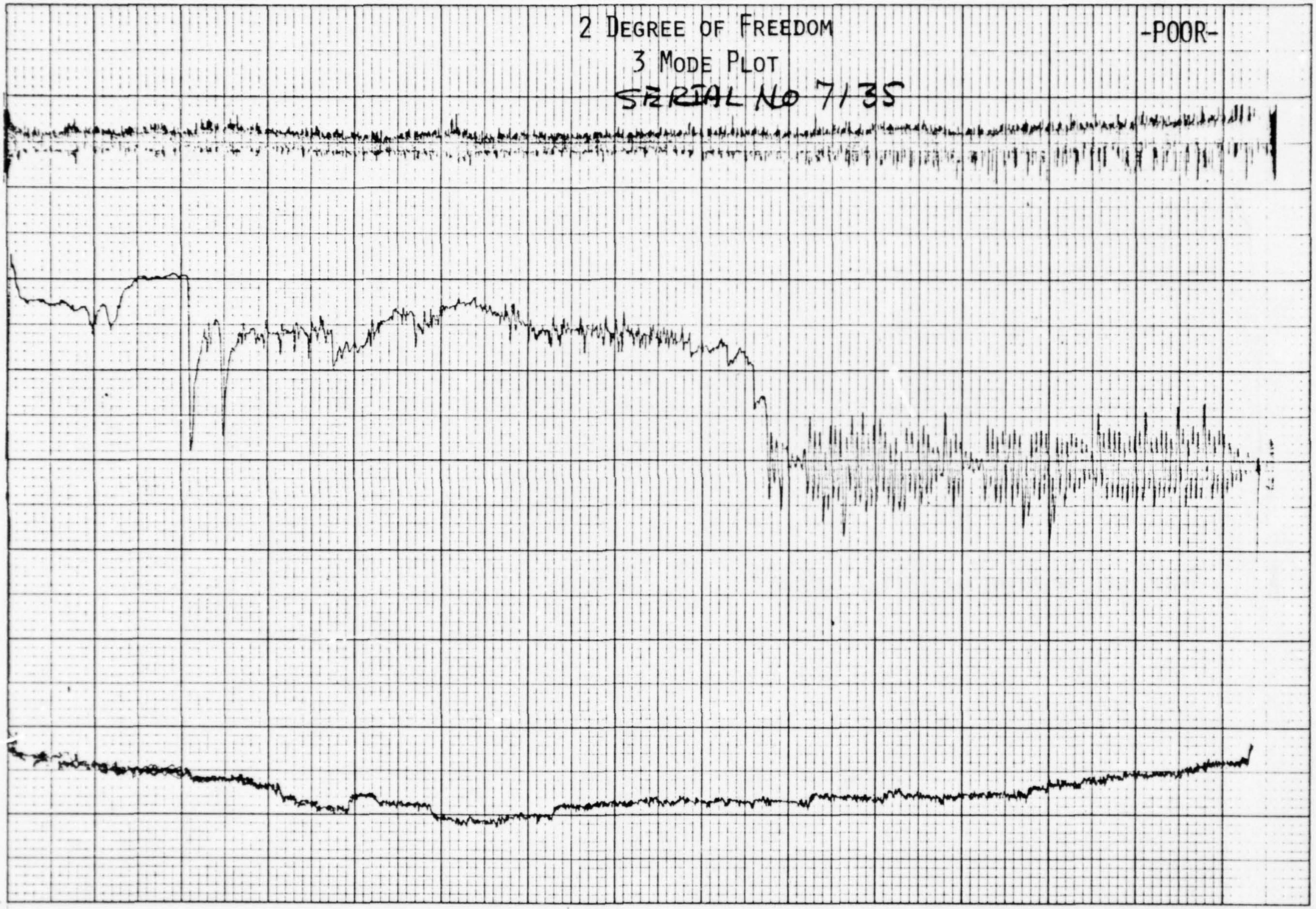
2 DEGREE OF FREEDOM GYRO
3 MODE PLOT

SERIAL NO 4778




2 DEGREE OF FREEDOM
3 MODE PLOT
-MEDIUM
Serial No 4728
14.4


-GOOD-
2 DEGREE OF FREEDOM
3 MODE PLOT
SERIAL NO 6968


2 DEGREE OF FREEDOM
3 MODE PLOT
SERIAL NO 7135
-POOR-

GAS BEARING GYRO

TEST ARTICLES

Quantity - 8
Configuration - straight journal, thrust plates (2)

TESTS

- All tested three orientations - SRA up, SRA down, SRA horizontal
- Special equipment: Midwestern high-speed strip chart recorder

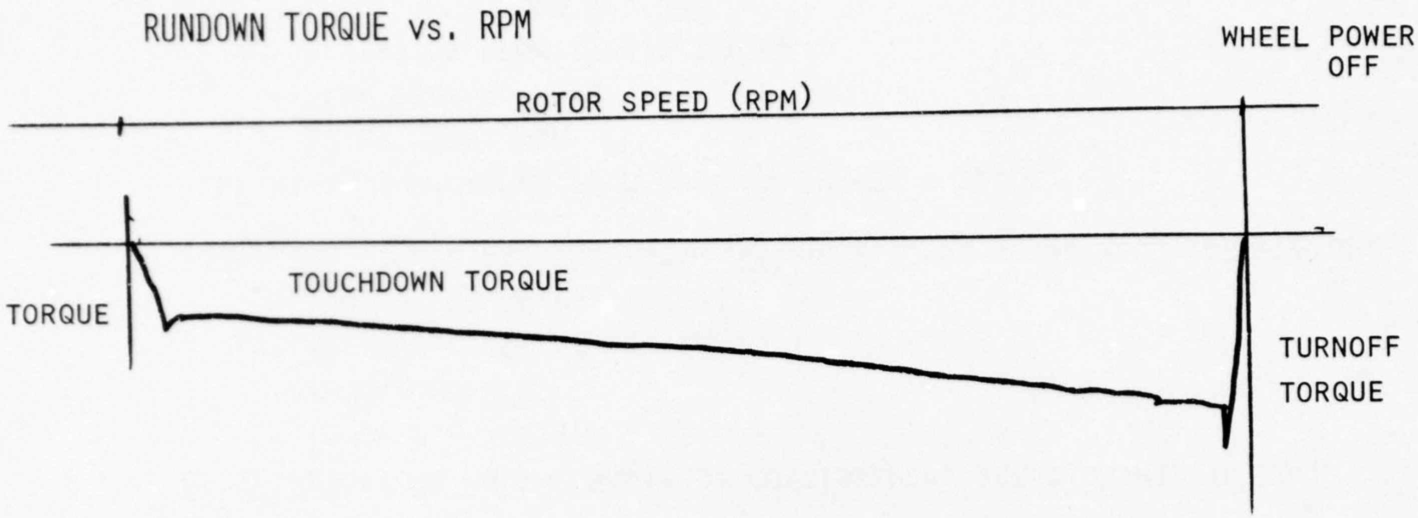
CONCLUSIONS

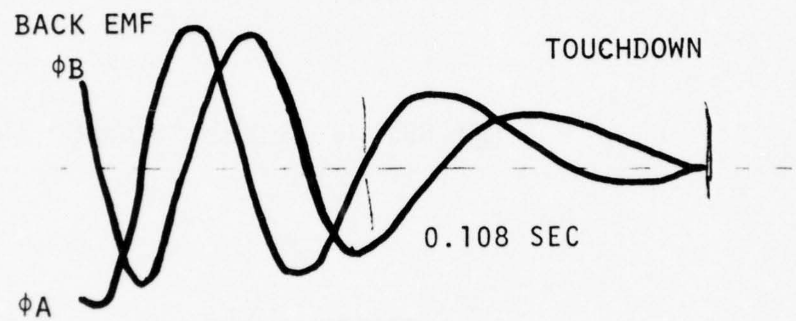
- Best indicators on the basis of consistency, relationship to mean
  - Touchdown torque*
  - Touchdown RPM*
  - Minimum starting voltage
  - Minimum breakaway torque

(* Touchdown torque and touchdown RPM were found to be well correlated.)

- Potential indicators from rundown traces include:
  - Spike magnitude
  - Hash peak-to-peak
  - Deviation from straight line
  - Slope of torque vs. RPM

GAS BEARING GYRO





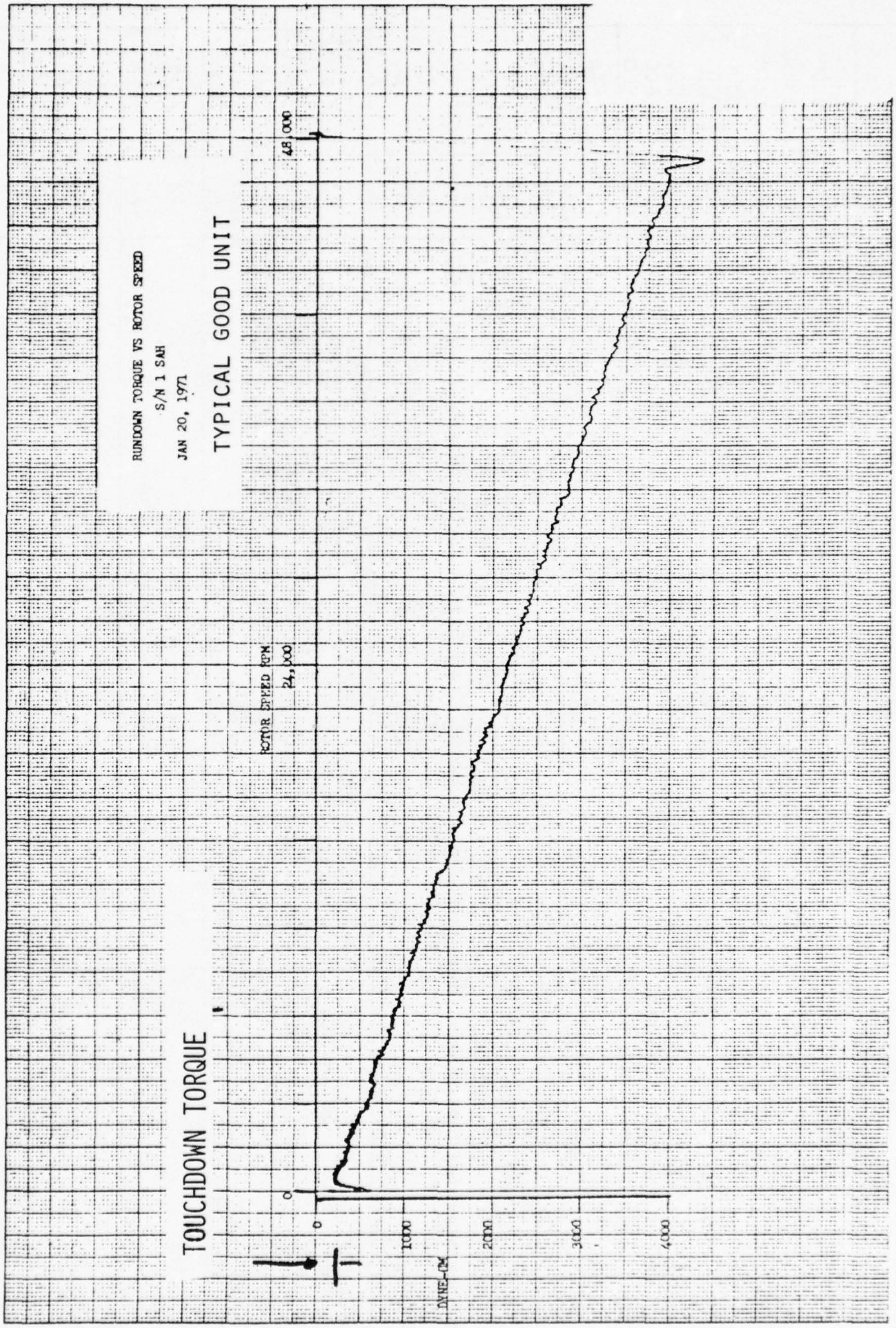
$$\text{AVE RPM} = \frac{0.5\ \text{rev}}{0.108\ \text{sec}} \times \frac{60\ \text{sec}}{\text{min}} = 278$$

$$\text{TOUCHDOWN RPM} = 278 \div 2 = 139$$

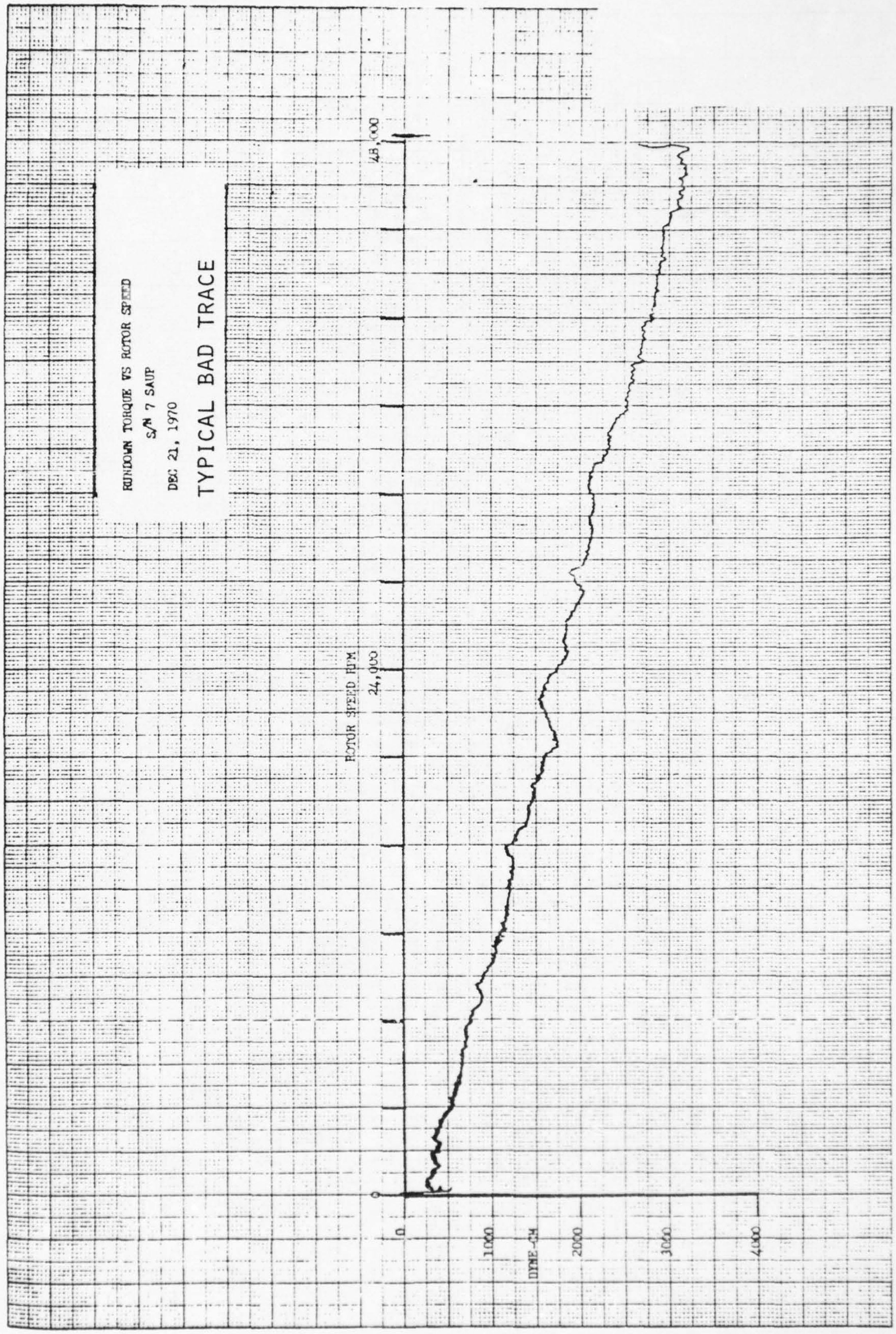
GYRO PTMS EVALUATION TEST RESULTS

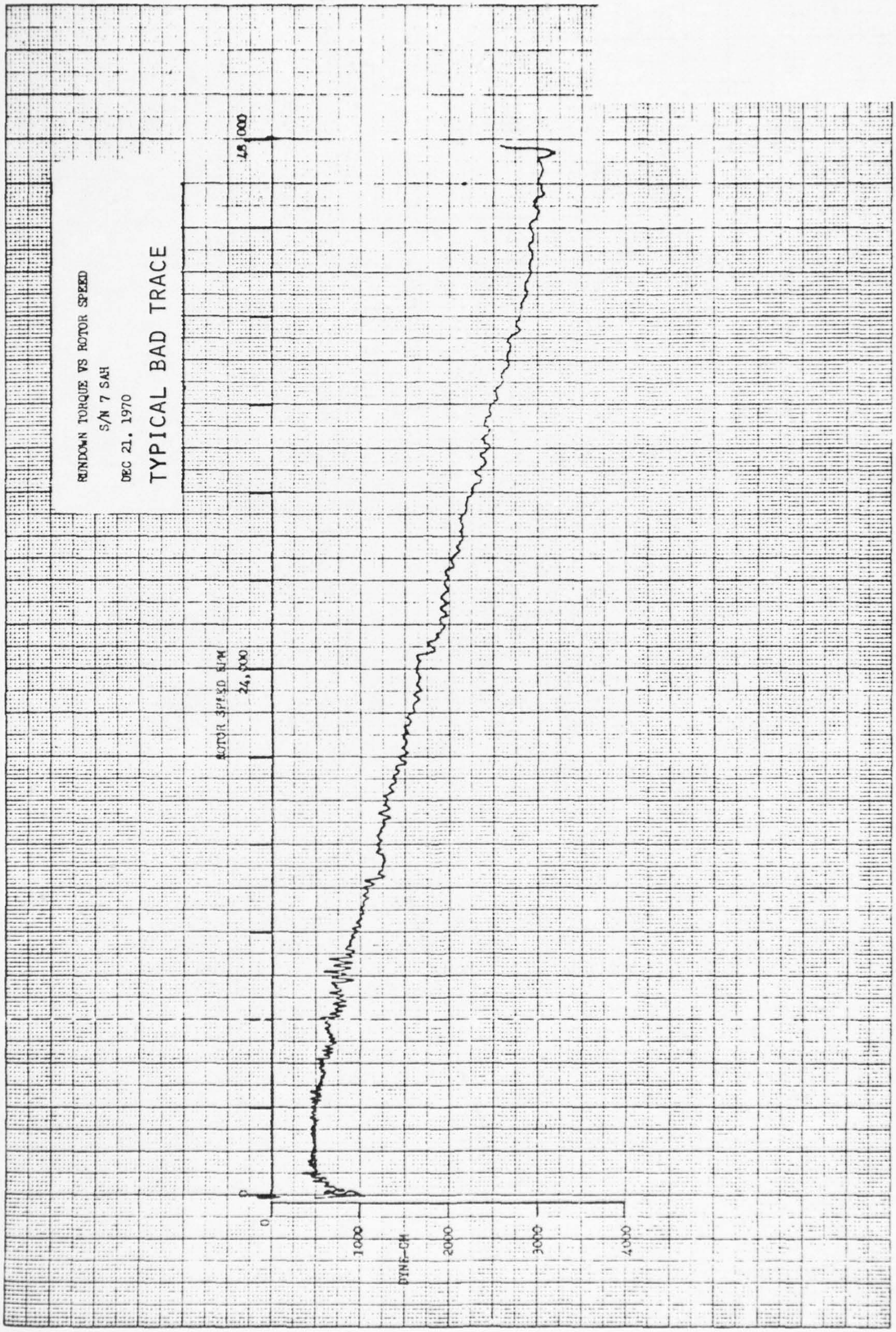
SERIAL NUMBERS

PARAMETER		1	2A	3	4A	5A	6	7	8
START TORQUE D-CM: 26V	SAUP	2240	1600	3000	4000		4016 @27	3320	4400
	SADN	2080	2000	3000	4000		3650	3200	4400
	SAH	2160	1600	3000	3700		3840 @27	3152	4400
SYNC TORQUE D-CM: 26V	SAUP	3840	3100	3200	3400		3024 @27	2960	3400
	SADN	3840	3000	3400	3200		2880	3040	3500
	SAH	3920	3000	3000	3200		2984 @27	3100	3400
TOUCHDOWN TORQUE D-CM	SAUP	560	1400	600	1000		2440	600	700
	SADN	4000	600	800	600		1160	2720	800
	SAH	560	1000	600	800		2552	920	800
TOUCHDOWN RPM	SAUP	65	89	69	87	264	125	73	60
	SADN	63	72	89	73	242	95	152	80
	SAH	65	77	76	73	225	128	89	80
RUNUP TIME SEC.	SAUP	40	50	19.5	14	12 @35V	13.6 @27V	16	13.5
	SADN	42	50	19	13	12 @34V	15.5	15	13.5
	SAH	46	54	19	13.5	11 @32V	13.8 @27V	15	13.5
RUNDOWN TIME SEC.	SAUP	44	50	47	45	31 @35V	42	48	44
	SADN	45	54	45.5	43	32 @34V	51	37	44
	SAH	46	48	47	43	35 @32V	45	41	43
MINIMUM START VOLTAGE	SAUP	21,21,21	26.5,27,28.4	22.5,23,23	17.5,17.5,17.5		27	20	17,17,17
	SADN	20,20,20	25,25,25	23.5,23.5,23.5	17,17,17		22.5	25.5	18,18,18
	SAH	21,21,21	25,25,25	19.5,19.5,19.5	17,17,17.5		27	21	17,17,17.6
MINIMUM BREAKAWAY TORQUE D-CM	SAUP	800	1800	1720	613		4016	9960	640
	SADN	560	1490	2000	587		2160	3120	1040
	SAH	720	1400	1800	567		3840	1120	800
MINIMUM SYNC SAUP	VRMS	25.0	28	23.5	22		27	22	21.5
	I MA	123	170	162	111		169	130	118
START T	D-CM	1840	2200	2000	2000		4016	2100	2320
SYNC DROPOUT	VRMS	19.5	15.3	14.5	<15		13.7	12.3	<14
	I MA	115	115	121	100		105	92	75
SYNC PWR	WATTS	3.7	3.9	4.6	3.2		4.1	3.5	3.2
HUNT FREQ	HZ	-	-	8	8		8	8	8



RUNDOWN TORQUE VS ROTOR SPEED
S/N 1 SAH
JAN 20, 1971
TYPICAL GOOD UNIT
TOUCHDOWN TORQUE
ROTOR SPEED RPM
0
24,000
48,000
0
1000
2000
3000
4000
DYNE-CM


RUNDOWN TORQUE VS ROTOR SPEED
S/N 7 SAUP
DEC 21, 1970
TYPICAL BAD TRACE
48,000
ROTOR SPEED RPM
24,000
0
0
1000
DYNE-CM
2000
3000
4000


RUNDOWN TORQUE VS ROTOR SPEED
S/N 7 SAH
DEC 21. 1970
TYPICAL BAD TRACE
48,000
ROTOR SPEED RPM
24,000
0
0
1000
2000
3000
4000
DYNE-CM

CLOSING COMMENTS

1. EXAMPLES OF PTMS DATA PRESENTED ILLUSTRATE THE PTMS FLEXIBILITY AND ITS ABILITY TO DETECT INCIPIENT FAILURE CONDITIONS.

2. SIMILAR RESULTS MAY BE OBTAINED BY OTHER TEST EQUIPMENT; HOWEVER, THE PTMS PROVIDES A COMPLETE VISUAL PICTURE WHICH CAN BE USED TO ANSWER QUESTIONS UNANSWERED BY DISCRETE MEASUREMENTS SUCH AS RUNDOWN TIME.

3. TORQUE MEASUREMENT CAPABILITY COULD BE INCORPORATED INTO LOW FRICTION, LOW INERTIA GYRO TEST TABLES.

4. USE OF THE PTMS (OR EQUIVALENT) AS A SCREENING TOOL BY ANY GYRO VENDOR, GYRO USER, OR GYRO REPAIRER WOULD RESULT IN MORE CONSISTENT SPIN AXIS BEARING QUALITY. (THE PTMS WOULD IMPROVE THE SELECTION PROCESS INCREASING THE PROBABILITY OF MAKING THE CORRECT DISPOSITION. THE ACTUAL SELECTION CRITERIA IS DEPENDENT UPON THE GYRO DESIGN AND ITS APPLICATION.)

5. USE OF PTMS (OR EQUIVALENT) AS A RESEARCH TOOL SHOULD LEAD TO A BETTER UNDERSTANDING OF BEARING DESIGN PARAMETERS AND BEARING DYNAMICS WHICH AFFECT BEARING RELIABILITY.

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DEMAGNETIZED RUNDOWN ANALYSIS FOR GAS BEARING RELIABILITY

19 NOVEMBER 1975

ROBERT J. SCHIESSER

11/75 CD7677

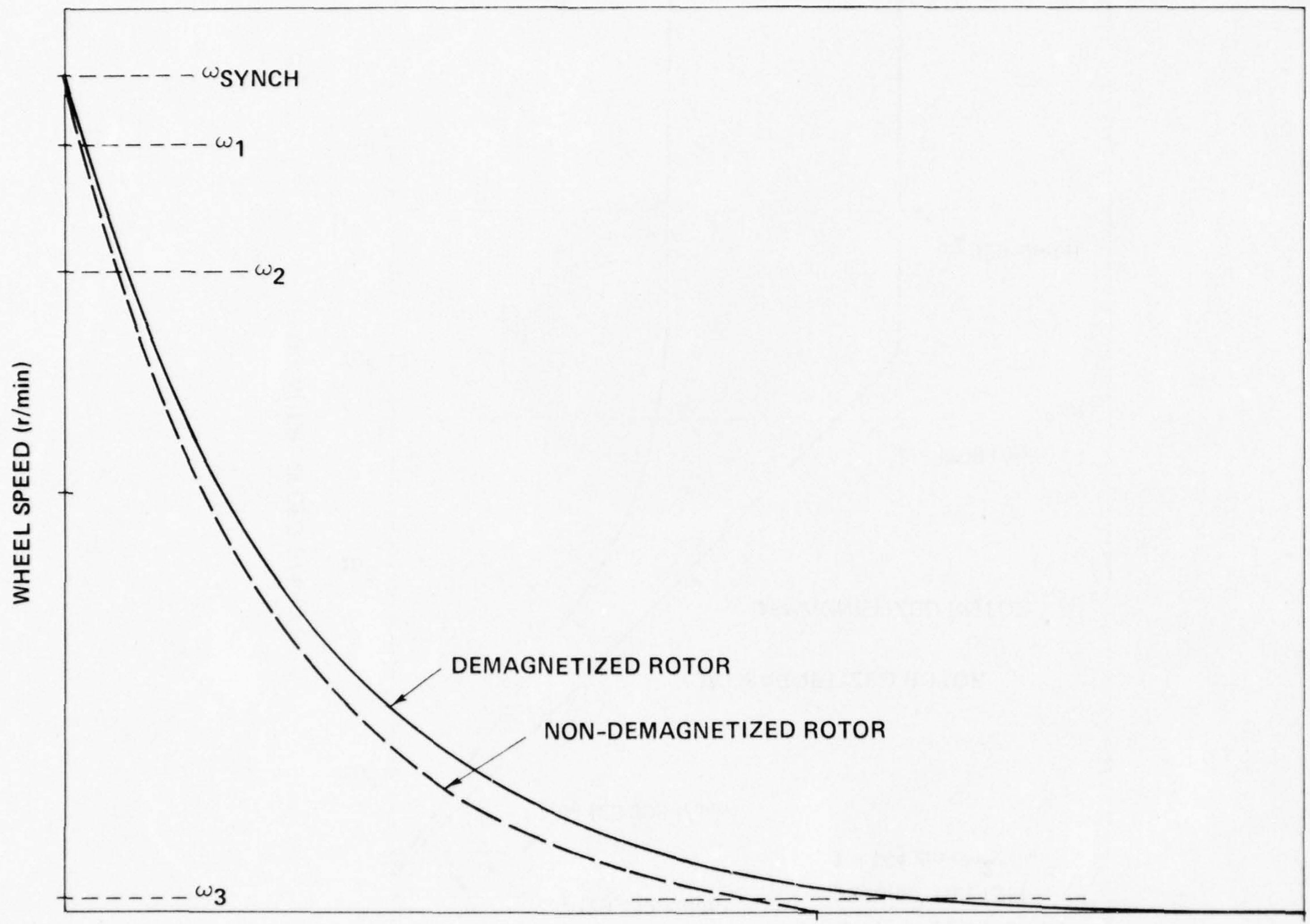
DECELERATING ROTOR

TORQUE ~ ROTOR MECHANICAL LOSSES

+ ELECTROMAGNETIC (CORE) LOSSES

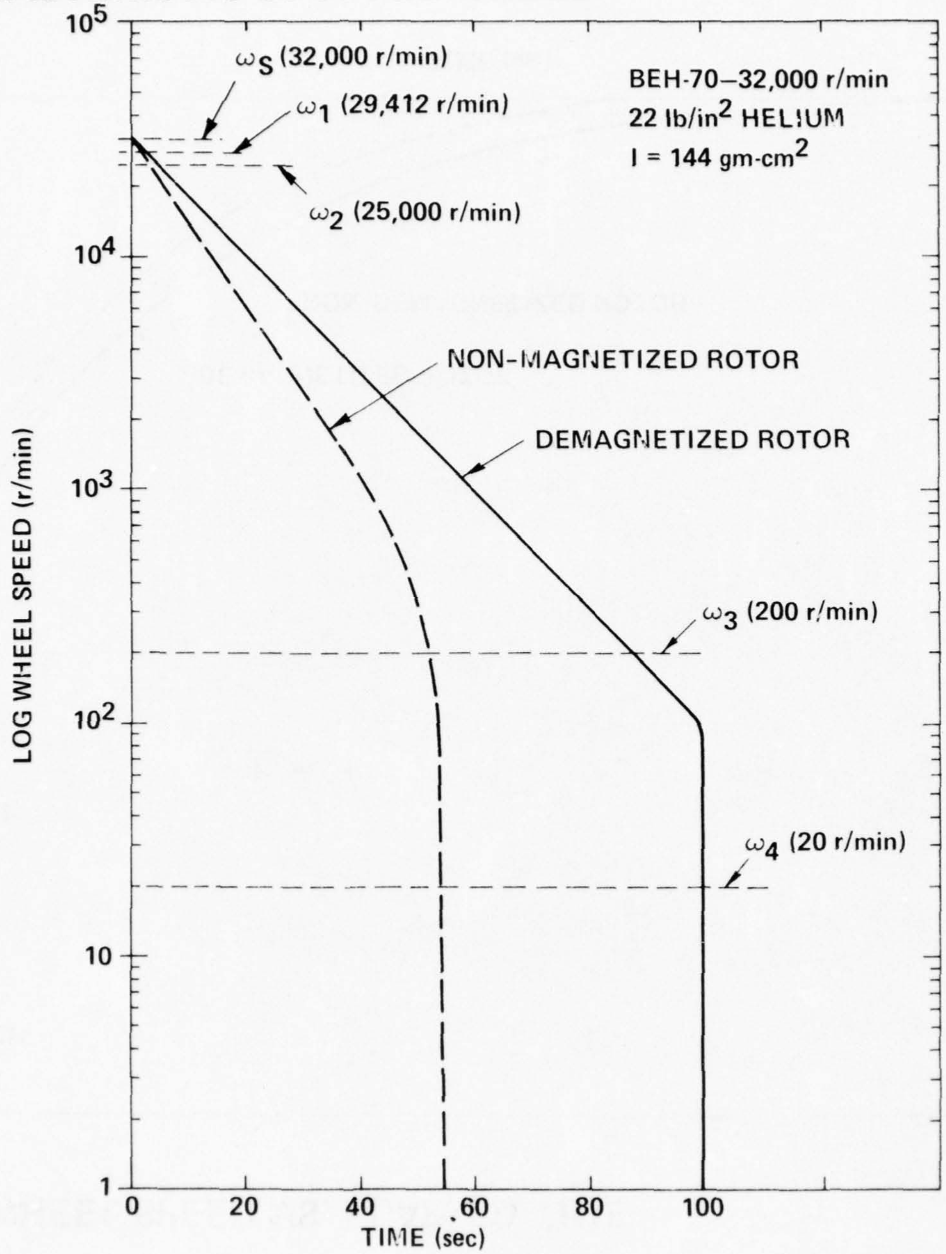
10/75 CD7387

TYPICAL WHEEL SPEED VS. ELAPSED TIME



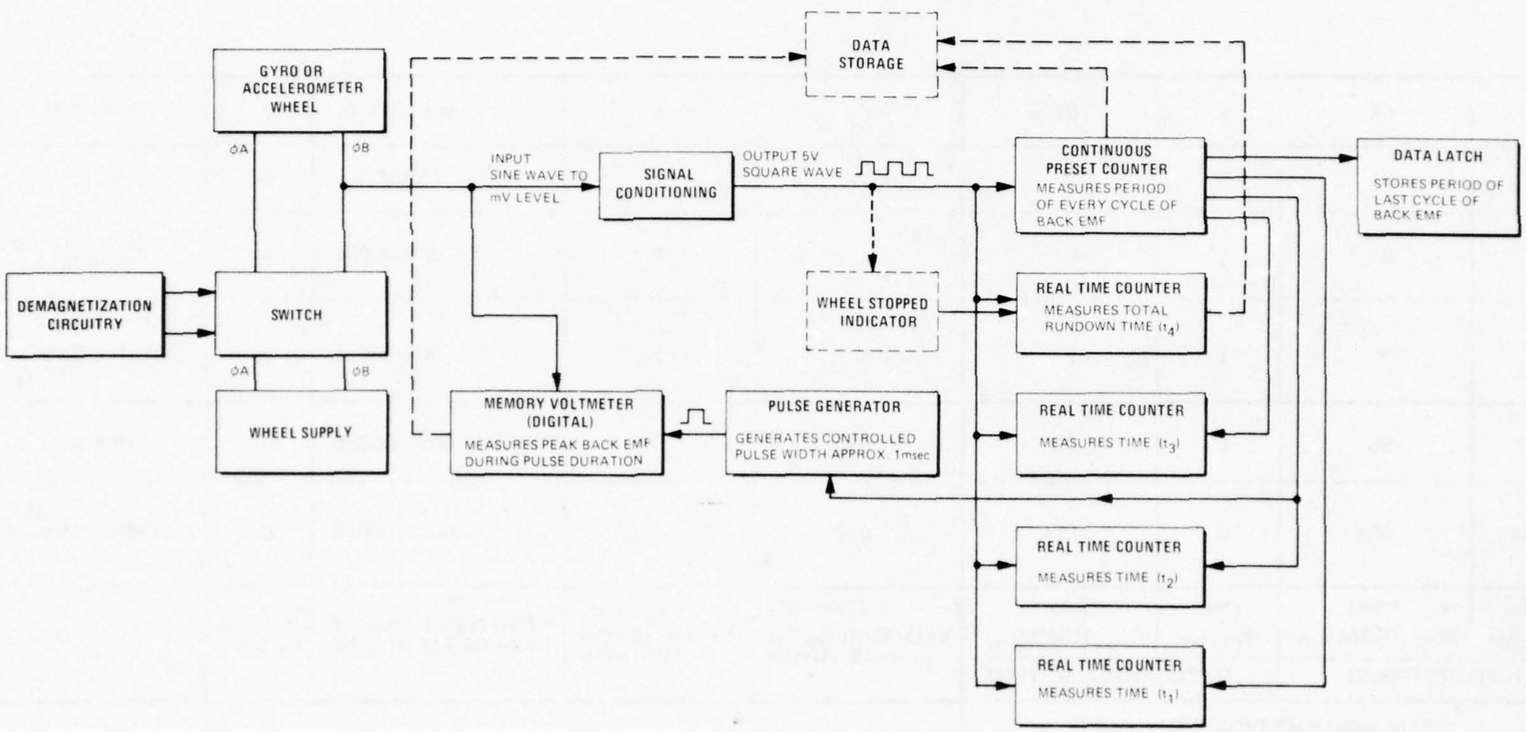
10/75 CD7312

RUNDOWN CHARACTERISTIC OF A TGG WHEEL



9/75 CD7289

DEMAGNETIZING RUNDOWN ANALYZER



9/75 CD7288

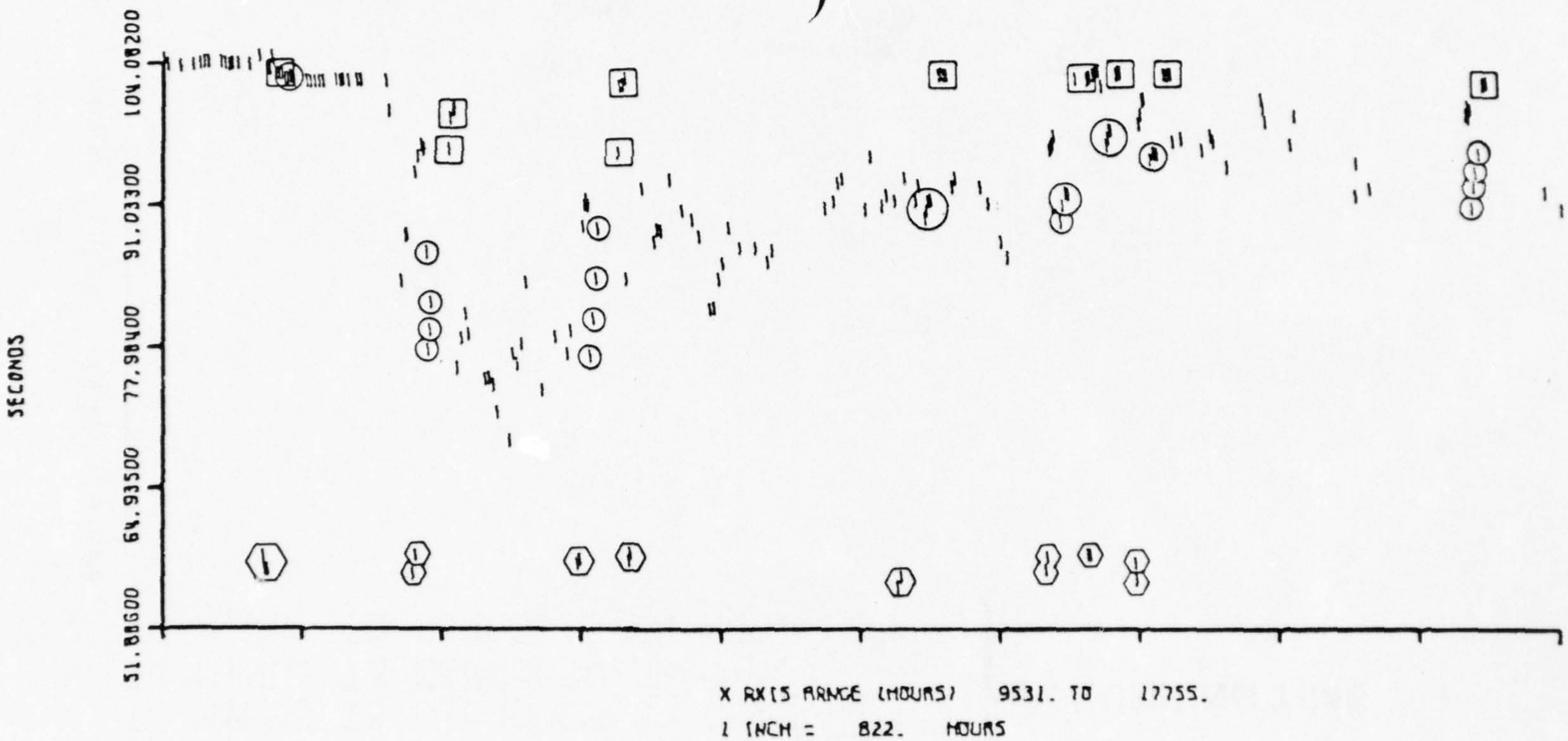
TYPE	MOTOR POLES	ROTOR SPEED (rpm) SUPPLY FREQ (Hz)	NOMINAL ROTOR WEIGH (gm)	NOMINAL ROTOR INERTIA (gm-cm^2)	TYPICAL DECELERATION TIMES: NON-DEMAGNETIZED ω_{SYNCH}/ω_3 (sec)	NON-DEMAGNETIZED ω_3/ω_4 (sec)	DEMAGNETIZED ω_{SYNCH}/ω_3 (sec)	DEMAGNETIZED ω_3/ω_4 (sec)
25 MOD 3 (SPOOL AND THRUST) PLATES)	6	24000/1200	120	210	110	9	160	20
TGG (SPHERICAL)	6	32000/1600	55	150	55	3	95	11
16 MOD G (SPOOL AND THRUST PLATES)	6	16000/800	4	1.2	4	1	5.5	2
B_4C (SPOOL AND THRUST PLATES)	6	16000/800	4	1.2	3	1	6	2
SOH (SPHERICAL)	6	16000/800	4	1.2	4	0.5	10	2
10 IRIG (SPHERICAL)	6	48000/2400	9	3.4	10	1	20	2.5

9/75 CD7287

BE-36 TW NO. 10

T3 NON-DEMAGGED SA HORZ
T3 DEMAGGED SA DOWN
T3 DEMAGGED SA UP
T3 DEMAGGED SA HORZ

vs. RUNNING TIME

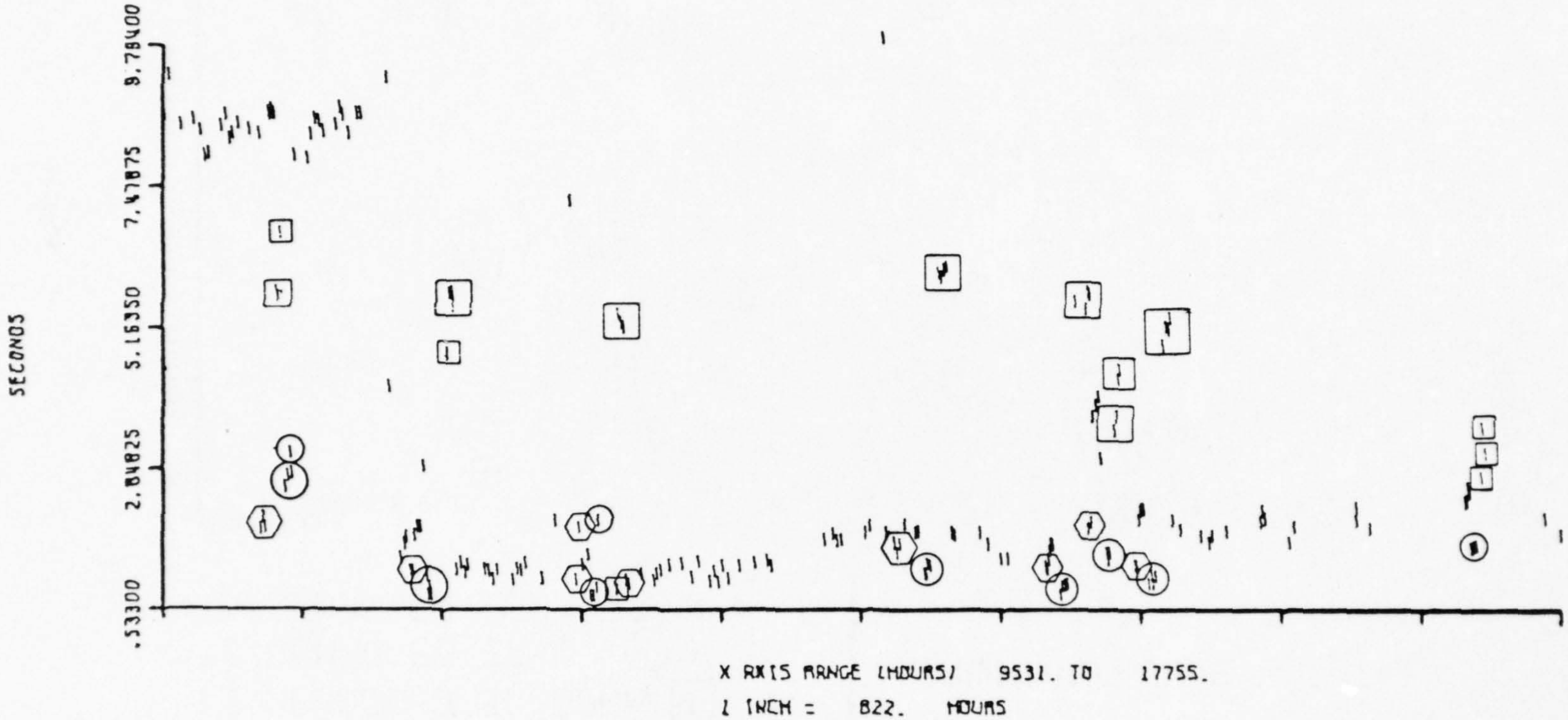


9/75 CD7302

BE-36 TW NO. 10

T4 MINUS T3 NON-DEMAGGED SA HORZ
T4 MINUS T3 DEMAGGED SA DOWN
T4 MINUS T3 DEMAGGED SA UP
T4 MINUS T3 DEMAGGED SA HORZ

vs. RUNNING TIME



9/75 CD7301

REDUCTION OF TORQUE UNCERTAINTIES

+

TIMING PRECISION

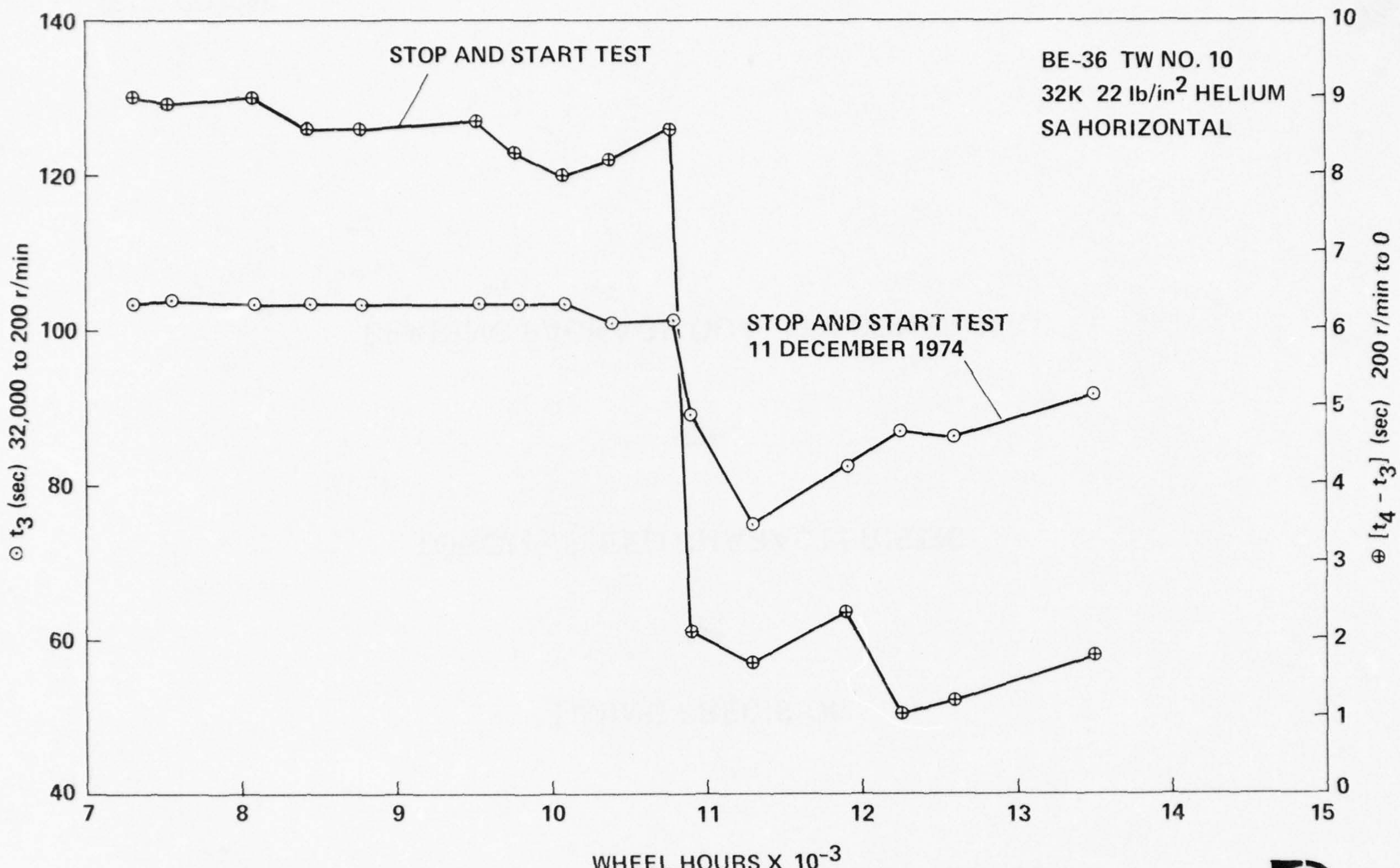
$\downarrow$

TORQUE/SPEED CHARACTERISTIC

$\downarrow$

BEARING PACKAGE QUALITY CONTROL

10/75 CD7388



STOP AND START TEST
BE-36 TW NO. 10
32K 22 lb/in² HELIUM
SA HORIZONTAL
STOP AND START TEST
11 DECEMBER 1974
⊙ t3 (sec) 32,000 to 200 r/min
⊕ [t4 - t3] (sec) 200 r/min to 0
WHEEL HOURS X 10-3

10/75 CD7311

NINTH DATA EXCHANGE FOR INERTIAL SYSTEMS

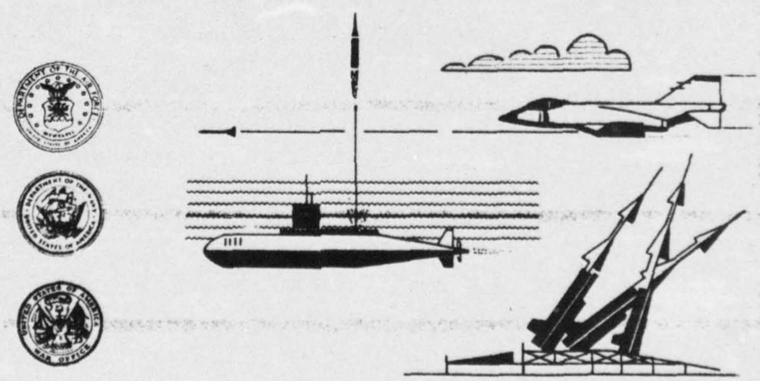
PLANNING GROUP

E. Bodem, Chmn	Air Force
R. Creed	Army
W. Denhard	Draper Lab
J. Fox	Navy
J. Grillo	Army
K. Kline	Navy
O. McClannan	Navy
R. Perdzock	Air Force
W. S. Smoot	Airlines
P. Zagone	Air Force

SOFTWARE WORKSHOP

NOV. 18 – 19 1975

Joint Services
Data Exchange Group
for
Inertial Systems



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ST. PETERSBURG FLA.

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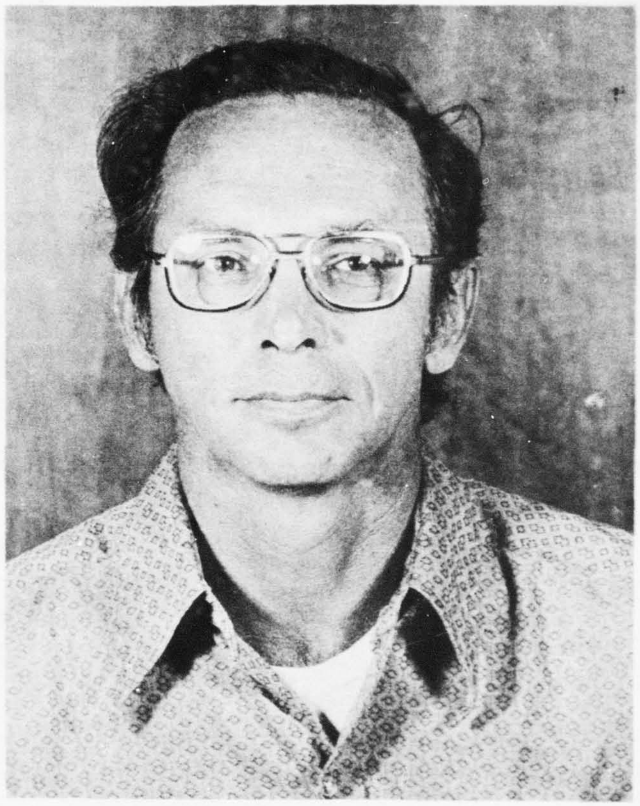
SOFTWARE WORKSHOP

WORKSHOP CHAIRMAN



DAVE KASPER

Mr Kasper has been associated with the Aerospace Guidance and Metrology Center (AGMC), Newark Air Force Station, Newark, Ohio, since October 1963. He was first employed as an Electronic Engineer in the Quality Engineering Branch. He was then promoted to the head, Gyro Engineering Unit, where he remained until 1966 when he was assigned the duties of head, Versatile Automatic Test Equipment Unit, which is now the Automatic Test Equipment Division of the Directorate of Service Engineering. Prior to transferring to AGMC, Mr Kasper was employed at the Naval Weapons Center, China Lake, California, in the test department from 1954 to 1963. While at China Lake, he held various management, staff engineering, and design engineering positions.

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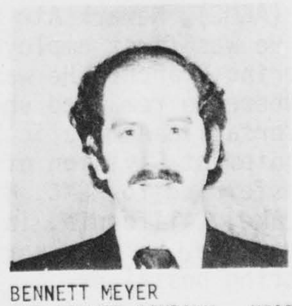

BENNETT MEYER
THE SINGER COMPANY - KEARFOTT DI

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NAVY ACCEPTANCE CRITERIA FOR ATE TEST PROGRAMS

STAN IAROSIS
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LAKEHURST, NEW JERSEY

The naval Air System Command specification, AR-9B, establishes the requirements for the development, test, documentation, configuration management, quality assurance, and preparation for delivery of ATE Test Program Sets. The term Test Program Set or TPS, as defined in AR-9B, is a collective term which groups and identifies all the elements required to test a unit under test or UUT with automatic test equipment. These TPS elements are defined as:

1. The Test Program Tape which contains the coded sequence which is executed by the ATE computer.

2. The Interconnection Device which provides the electrical and mechanical compatibility between the ATE system and the UUT.

3. The Test Program Instruction which provides ATE operator with instructions for preparing the UUT for testing, connecting the UUT and the Interconnection Device to the ATE, accomplishing the as-programmed test, removing the UUT and the Interconnection Device from the ATE, and the disposition of the UUT.

The Navy's acceptance of an ATE test program is dependent on the capability of the TPS to successfully perform the required level of fault isolation on the UUT for which the test programs were written, thereby demonstrating the integration of the ATE system, TPS elements, and the UUT. Although a formal acceptance test procedure is conducted for each TPS, the acceptance or rejection of a TPS is determined at different milestones in the TPS design/development cycle. This TPS design/development cycle is depicted in figure (1) and described as follows:

1. Phase I tasks involve:

   a. The contractor generation of UUT source data (schematics, assembly drawings, engineering specifications, and test requirement documents) with Navy approval of content and format.

   b. Navy and contractor performance of support equipment compatibility studies.

   c. Contractor submission of support equipment recommendations to the Navy.

2. Phase II begins with the Navy approval of the support equipment requirement recommendation. Assuming that the support equipment is ATE, phase II will include:

   a. Contractor generation of program design data with Navy review of its content and format. This program design data includes the following:

      (1) A diagnostic flow chart which is the UUT test oriented flow chart representing the UUT test strategy being implemented on the ATE.

      (2) A test diagram which identifies the electrical path between the UUT and ATE, and is prepared for each test or group of tests that have the same basic test set up.

      (3) An ATE source program which is the complete, detailed programmed description of each step in the testing of a given UUT prepared in the source language. It reflects the requirements collectively established in the diagonstic flow chart, test requirement document, and the test diagram.

   b. Contractor design, development, debug and integration of the TPS elements with Navy monitoring.

   c. TPS acceptance test performed by the contractor and supervised by the Navy.

3. Phase III is the delivery, on-site verification and up-dating/revising the production test program set.

Specification AR-9B provides for government engineering personnel to supplement the local on-site government inspection service, i.e. DCAS, NAVPRO, AFPRO, etc. at the contractor's plant to review UUT source data, review program design data, monitor Test Program Set debug and integration, and review, supervise and approve the acceptance testing for each Test Program Set. The Naval Air Systems Command has tasked the Naval Air Engineering Center to provide this engineering assistance. This engineering team reviews all the supporting data to assure that the TPS meets the following criteria:

1. Exercise all UUT Functional Inputs.

2. Exercise all distinct/unique UUT operating Modes but avoid redundancies.

3. Evaluate (i.e., detect degradation) all UUT functional outputs including BIT. After performance routine is all "go", a BIT test should be performed to insure BIT good.

4. Evaluate only those UUT Test Points that monitor UUT function outputs "not directly" measurable by ATE.

5. Detect degradation at the UUT functional (not Test Point) interface of any UUT operational performance having an impact upon performance of a high order assembly/system (i.e. UUT).

6. Minimize UUT set-up, Test, and tear-down times.

7. Include automatic branching of diagnostic fault isolation type routines.

8. Minimize legthy time-delays (perform other tests during execution of time-delays).

9. Minimize/Optimize operator action/Intervention provided same is deemed to be "absolutely necessary".

10. Provide for rapid "visual" evaluation of UUT status desplays, indicator and operation of UUT Environmental Functions.

11. Include at all test program Entry Points:

    a. ID Signature Test - verifying under program control the presence of resistances inserted into the ID soley for this purpose.

    b. UUT Signature Tests.

    c. Safe-to-turn-on test-detect the possibility of shorted or open lines at the UUT connector that may damage the UUT, ID or ATE.

    d. Power-Application Sequence (if applicable)

    e. ATE reset sequence prior to and upon completion of UUT testing.

12. Be as short, rapid and straight forward as possible.

13. Stress detection of faults at the UUT functional Input/Output (rather than test point) Interface i.e. observe UUT outputs to the next higher level Assembly.

In addition the performance routine of the TPS shall not:

1. Evaluate test points peculiar to UUT diagnostic fault isolation.

2. Rely on BIT

3. Evaluate UUT power supplies (unless critical to or degrade UUT outputs).

4. Include any in line diagnostic routines.

5. Include verification of UUT functionsl input signals at the ATE interface.

6. Include time consuming measurements.

7. Include probing.

8. Include in line repair actions other than adjust/align types while on-line with ATE tracking.

9. Include time consuming tracking, power, search, maxima/minima type measurements unless they are deemed absolutely essential to UUT performance verification.

10. Include time consuming operator observations during on-line ATE testing for evaluation of the followint:

    a. ATE displays.

    b. Complex UUT display patterns and indications (i.e. unless same are deemed absolutely essential to UUT performance verification.

This effort by the Naval Air Engineering Center assures with some confidence that the TPS has been designed in accordance with AR-9B and that it is ready for acceptance testing. The objective of the acceptance test is to demonstrate to the Navy the fault detection and isolation capabilities of the TPS by insertion of faults in the UUT. A sampling plan is used to prove the acceptability of the TPS. The parameters used for this plan are:

1. An acceptable quality level of 2.5%

2. A limiting quality of 13.0%

3. Customers Risk and Producers Risk varying from 1% to 25% according to the contracted MTBMA (Mean Time Between Maintenance Actions) for the UUTs to which the TPS applies. See Figure 2.

These parameter values are used to develop a chart for each TPS. This chart and the formulas to develop the chart is shown in Figure 3. Utilizing a completed chart, a running graph of faults inserted versus defects is kept and a Navy decision is made to accept or reject the TPS depending on whether the plot tends into the accept or reject region. The decision can be made at any time after the minimum number of faults have been inserted, but can be deferred until the maximum number of faults have been inserted and the results recorded. The maximum number of faults is 1.5 times the minimum which in turn is defined by the

integer number greater than

The faults inserted are selected by the Navy. The contractor, however, provides the Navy with a list of faults from which are selected the candidate faults. An example of a contractor fault sample selection list is shown in Figure 4. The Navy selects the faults randomly from this list. After the faults are selected, the contractor and the Navy review the candidates and exclude those faults that cannot be simulated at the piece part level, will not be reflected at the UUT interface or will damage the UUT. If after the above review, the list of faults does not equal the required number, additional faults will be selected and reviewed until the number equals or exceeds the maximum number of faults to be inserted.

Following a successful acceptance test, the Naval Air Engineering Center Representative recommends acceptance of the TPS by the local government on-site inspection service.

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EFREM G. MALLACH

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MICROPROGRAMMING: WHAT AND WHY?

The term "microprogramming" has been used a lot - perhaps overused - in the past few years. Listening to some speakers, reading some articles, one could get the impression that it will revolutionize computers, and that anyone not expert in it is hopelessly out of date. This just is not so. In this paper, we will bring microprogramming down to earth. We will show that it's just another computer design tool, though an important one, with its plusses and minuses. Last, we will discuss what some of these plusses and minuses are, and how they might impact ATE.

Let's look at how a computer's central processor might be organized. A simplified block diagram is shown in Figure 1. The instruction register is loaded with an instruction from a memory location given by the program counter. Based on the instruction, control logic then drives the memory and the ALU in executing the instruction. (Various paths, not shown, lead back to the program counter to permit branching.) After the instruction is executed, the next one is fetched, and the cycle repeats.

Each instruction involves many internal steps. Consider what must be done to carry out an "add" instruction in a simple minicomputer:

1. Obtain the instruction from memory.
2. Put the instruction address field in an address register.
3. If the instruction "index bit" is 1, add the contents of the index register to the address register.
4. If the instruction "indirect bit" is 1, use the address register to obtain a memory word and place that word in the address register.
5. Use the address register to obtain a memory word and place that word in one adder input register.
6. Place the contents of the accumulator in the other adder input register.
7. Place the contents of the adder output register into the accumulator.
8. If a carry occured, set the carry bit.
9. If overflow occured, set the overflow bit; then if overflow traps were not masked, cause an overflow trap.
10. Repeat by fetching the next instruction.

This is for a simple instruction on a simple computer. We can complicate matters by considering, say, a floating-point operation, or by enhancing the machine with multiple index registers, multiple accumulators, base registers, relocation... and the logic needed to control moving data around the machine, controlling conditional activities, etc., becomes very complicated. This logic is hard to design, is prone to obscure errors, and is devilish to check out. Is there a better way?

One answer to this question is "microprogramming." The term was first used by Maurice Wilkes of Cambridge U. in England in 1951. In fact, he called his paper "The Best Way to Design an Automatic Calculating Machine." His con-

cept was to regularize the control logic by designing, in effect, a bare-bones computer inside the user visible computer. The instructions of this computer were called "microinstructions," which combined to form a "microprogram." Each bit of a microinstruction controlled a gate or gates in the ALU directly. Wilkes' scheme virtually eliminated the need for specialized control logic: the user-visible computer didn't need it, because the microprogram took its place; the inner computer didn't need much, because it was very simple and was designed purely for ALU control.

Microprogramming was little used in practice for many years. As technology evolved, though, the necessary components (especially fast storage for the microprogram) became more economical than control logic. Growing complexity of instruction sets helped this trend. By the late 1960's, microprogramming was accepted as a commercially viable way to design the control function of a computer. Today, the majority of new systems use this method.

At this point we should separate "microprogramming" from "microprocessors." A microprocessor, in today's sense, is an LSI* chip (or a small set of LSI chips) that form(s) the logic portion of a small computer. A microprocessor might happen to be microprogrammed - the pros and cons of microprogramming hold there as well as for other types of processor - but it doesn't have to be. The confusion arises, first, because the terms are so similar (and it's too late to change either one;) and, second, because some people used the term "microprocessor" to mean "the inner computer that executes the microprograms" before modern LSI microprocessors came into being. It's important to keep these terms straight.

Another term we should define is "firmware." This term was coined by Ascher Opler to refer to microprograms because they stand between the hardware and the software. Just as the set of physical elements which form a machine are its "hardware" and the set of programs it executes are its "software," the set of microprograms that control a computer are its "firmware." Firmware, then, means microprograms.

Now that we've defined our terms, what are some of the pros and cons of microprogramming (or firmware)?

Advantages:

- Ease of design. A complex instruction set can be implemented and checked out more easily than with hard-wired control logic.

- Ease of changes. Since the meaning of each instruction is defined by a program, this program can be changed.

- Ease of extensions. If the design of a computer allows for it, microprograms can be added to perform functions that the original designers did not include. This capability can specialize the instruc-

*Large Scale Integration. Refers to semiconductor technology that permits combining hundreds of logic elements in a component typically a few mm square.

tion set for a particular class of applications. It can also be used to make one machine run programs written for (or "emulate") another machine, though performance will be poor if the machines are not quite similar.

- Ease of diagnosis. The microprogram interacts directly with the ALU, not through complex control logic. It is possible to write diagnostic microprograms that can run when the ALU has failed (and software couldn't run), and can localize a failure more effectively than software could.

Disadvantages:

- Performance. Microprogrammed machines are usually slower than a compatible system, using hard-wired control logic and the same technology, would be. This is usually important only when the fastest available technology is used. Below this point, it is usually more economical to improve performance by other means while staying with a microprogrammed design.

- Cost for simple instruction sets. If a computer has a very simple instruction set, it is still economical to use hard-wired control logic.

What is the impact of microprogramming on ATE? There should be little or no direct impact. The ATE manufacturer embeds a minicomputer in an ATE system in the same way, regardless of whether that mini is or is not microprogrammed. The difference will be hidden from the ATE user. There is an indirect impact, though, in the following ways:

- The benefits of more cost-effective minicomputers are passed on to ATE users.

- Microdiagnostics can result in more reliable ATE.

- Custom microprogramming can provide specialized instruction sets to give simpler, faster and more compact ATE software.

Microprogramming is a major design feature of the computer in ATE. Its indirect impact on ATE users can be significant. An informed ATE user should be aware of microprogramming: what it is, and what it isn't; what it can do, and what it can't.

Suggestions for Further Reading

The reader who wants to delve further into microprogramming can investigate the following sources:

1. Books. Two textbooks devoted largely to microprogramming have been published. they are Microprogramming: Principles and Practice, S. S. Husson (Prentice-Hall, 1970) and Computer Organization and Microprogramming, Y. Chu (Prentice-Hall, 1972.) A number of papers on different aspects of the field are collected, and related to each other by the editors, in Infotech's State-of-the-Art Report on Microprogramming and System Architecture (Infotech Ltd., Berkshire, U.K., 1974.)

2. CS Overviews. Computing Surveys (CS) is the survey and tutorial journal of the Association for Computing Machinery (ACM.) It has published two papers on microprogramming: "The Growth of Interest in Microprogramming: A Literature Survey," M. V. Wilkes, vol. 1, no. 3 (September 1969), and "Contemporary Concepts of Microprogramming and Emulation," R. E. Rosin, vol. 1, no. 4 (Dec. 1969). This last paper will give you some of the flavor of microprogramming a real machine without all the pain.

3. Special journal issues. All the professional journals have, on occasion, published articles on microprogramming. For the browser, however, it is inconvenient to find them. Five journal issues have unusually high concentrations of microprogramming articles and should be easy to find. The earliest is the February 1964 issue of Datamation, worth reading today only for historical perspective. Next is the December 1965 issue of Communications of the ACM, which contains a number of articles on "emulation" - using microprogramming to enable one computer to execute programs originally written for another. Both more recent and more technical are the July 1971 and August 1974 issues of the IEEE Transactions on Computers, devoted entirely to microprogramming. The most recent special issue on microprogramming is the August 1975 issue of Computer, also published by the IEEE.

4. ACM SIGMICRO. The ACM's Special Interest Group on Microprogramming (SIGMICRO) publishes a quarterly newsletter (SIGMICRO Newsletter) containing reports of current research, conference summaries, press releases about microprogrammable computers, and the like. This newsletter also carries the most complete bibliographies available in the field. The issue appearing each July carries a bibliography for the preceding year, prepared by Dr. Louise Jones, and the September 1974 issue was devoted entirely to a combined bibliography going back to 1951. This group also co-sponsors annual workshops on microprogramming with the IEEE Computer Society. Proceedings or Preprints are available for most of them. (The papers in the two IEEETC issues mentioned in the previous paragraph are taken primarily from the third and sixth workshops, respectively.)

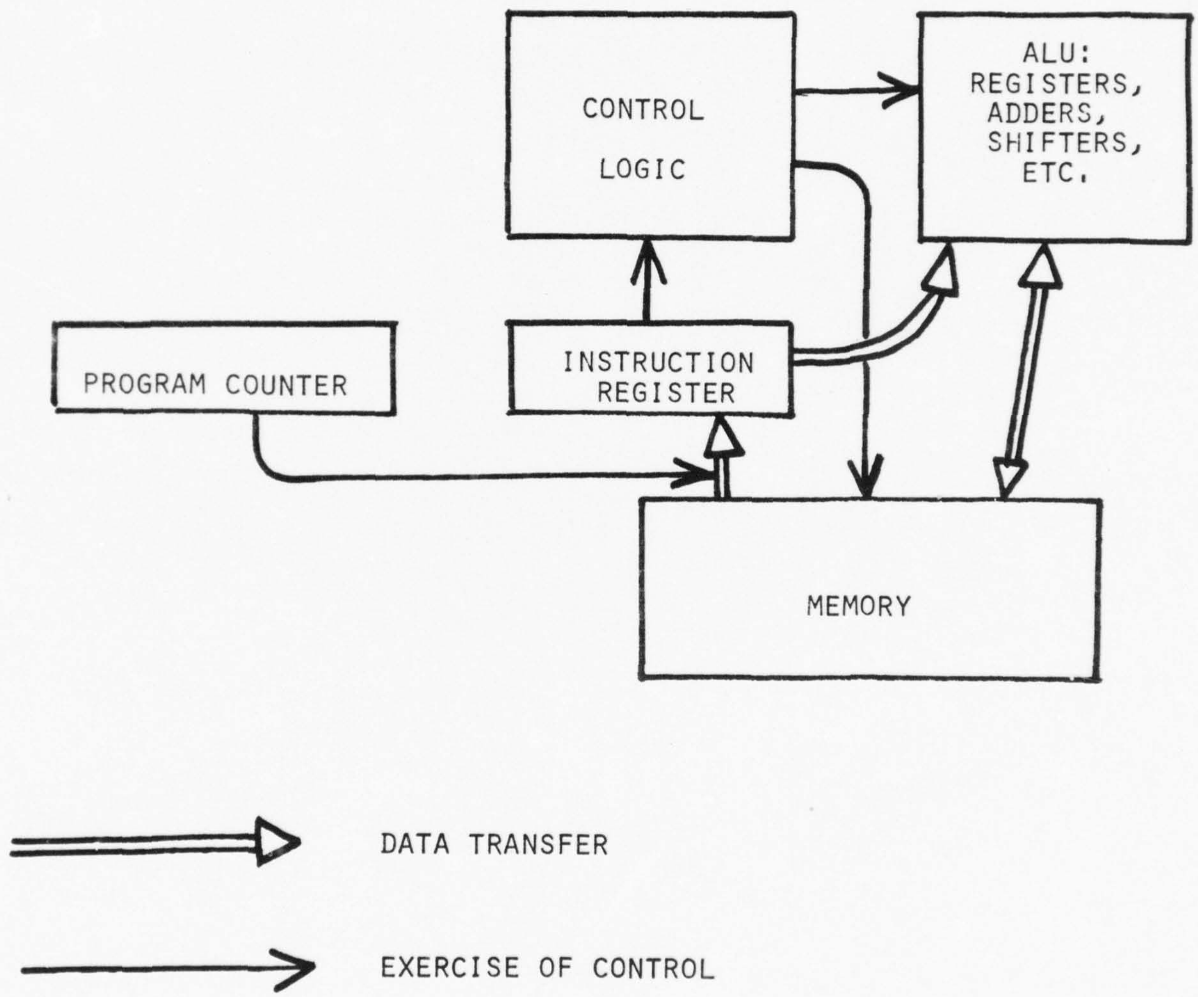

FIGURE 1

ORGANIZATION OF A NON-MICROPROGRAMMED COMPUTER

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MANUFACTURING TEST REQUIREMENTS VERSUS
REPAIR TEST REQUIREMENTS SOFTWARE IMPACT

MANUFACTURING TEST REQUIREMENTS
VERSUS
REPAIR TEST REQUIREMENTS
SOFTWARE IMPACT

Prepared By:

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J. J. Shepard
H. R. Turner

Prepared For:

Ninth Joint Services Data Exchange For
Inertial Systems Conference
Clearwater, Florida
18 - 20 November 1975

Rockwell International

Strategic Systems Division
3370 Miraloma Avenue
Anaheim, California 92803

X75-1026/201

MANUFACTURING TEST REQUIREMENTS VERSUS REPAIR TEST REQUIREMENTS SOFTWARE IMPACT

SUMMARY

Factory production test programs for navigation systems are written to verify functional capabilities of the product at various levels of the assembly process. Limited fault isolation routines are required due to this step-by-step method which reduces probability of failure at final assembly. A different approach is required at the depot since the situation is reversed. Systems are returned to the depot because of a field failure and the fault must now be verified and the failed unit or part identified. It is essential that depot test programs include fault isolation routines to reduce system turnaround time and reduce maintenance costs. If the initial factory test programs are properly modularized so existing subroutines can be linked with new fault isolation routines, then a substantial savings in cost and time can be achieved in providing the required programs to the depot. This method was used to provide MALVIR (Malfunction Verification Isolation Requirements) programs to Newark Air Force Station (NAFS) for maintenance of Minuteman III navigation systems.

INTRODUCTION

This paper discusses the basic differences in test requirements for manufacturing and depot testing of navigation systems and describes the software methods developed on the Minuteman III test programs to satisfy these requirements.

Since performance of functional tests is a requirement for both the depot and the manufacturer, the major differences in requirements exist in the area of diagnostic routines and system burn-in tests. Manufacturing test requirements for navigation systems are usually written with emphasis on functional testing with limited diagnostic test routines. Extensive system diagnostics are not required in the production phase partially because of the extent of lower level testing (module, instrument, subsystem) which reduces NO-GO's at system level where fault isolation is

more difficult and the availability of an experienced engineering staff to support manufacturing test operations when a fault occurs at the system level.

The test situation is reversed at the depot where the system is tested to verify (or identify) the field fault and isolate the faulty part. Diagnostic routines in this situation are essential to reduce system turn-around time which results in reduced maintenance costs because fewer spare systems and test stations are required to support the program.

In the production phase performance testing occurs at system level as a result of system burn-in requirements. To minimize system turn-around time at the depot, the emphasis is placed on performance of subsystem level tests. This philosophy aids the depot in effecting quick turn-around of systems by substitution of previously tested subsystems and the performance of a relatively brief system functional test.

While differences in test requirements may exist, a significant reduction in software cost can be achieved if the factory and depot test equipment are essentially the same and the factory software is developed in modular form. If these conditions exist, then common executive and test equipment self-test programs can be utilized. In addition, if the factory functional test programs are developed as a series of subroutines to perform specific functions (platform slewing, platform leveling, system initialization, etc), then these routines can be linked with new routines to form diagnostic or functional test routines for the depot.

MINUTEMAN III TEST SOFTWARE DESCRIPTION

The Minuteman III program utilizes the concept outlined above. Common test equipment is used at the factory and depot employing the same Executive program. (A description of the Executive software and test equipment developed by Rockwell International for the Minuteman III programs is presented in Appendix A.) Minuteman III test programs are divided into a set of test sequences which must be performed to satisfy total test requirements (e.g., the Missile Guidance Set (MGS) has a Performance Test Sequence and Functional Test Sequence). As shown in Figure 1, each sequence is further divided into modes. Each mode consists of subtests which must be performed to satisfy that mode. Each subtest is programmed at the subroutine level. Commonly used functions such as measurement data conversion, test

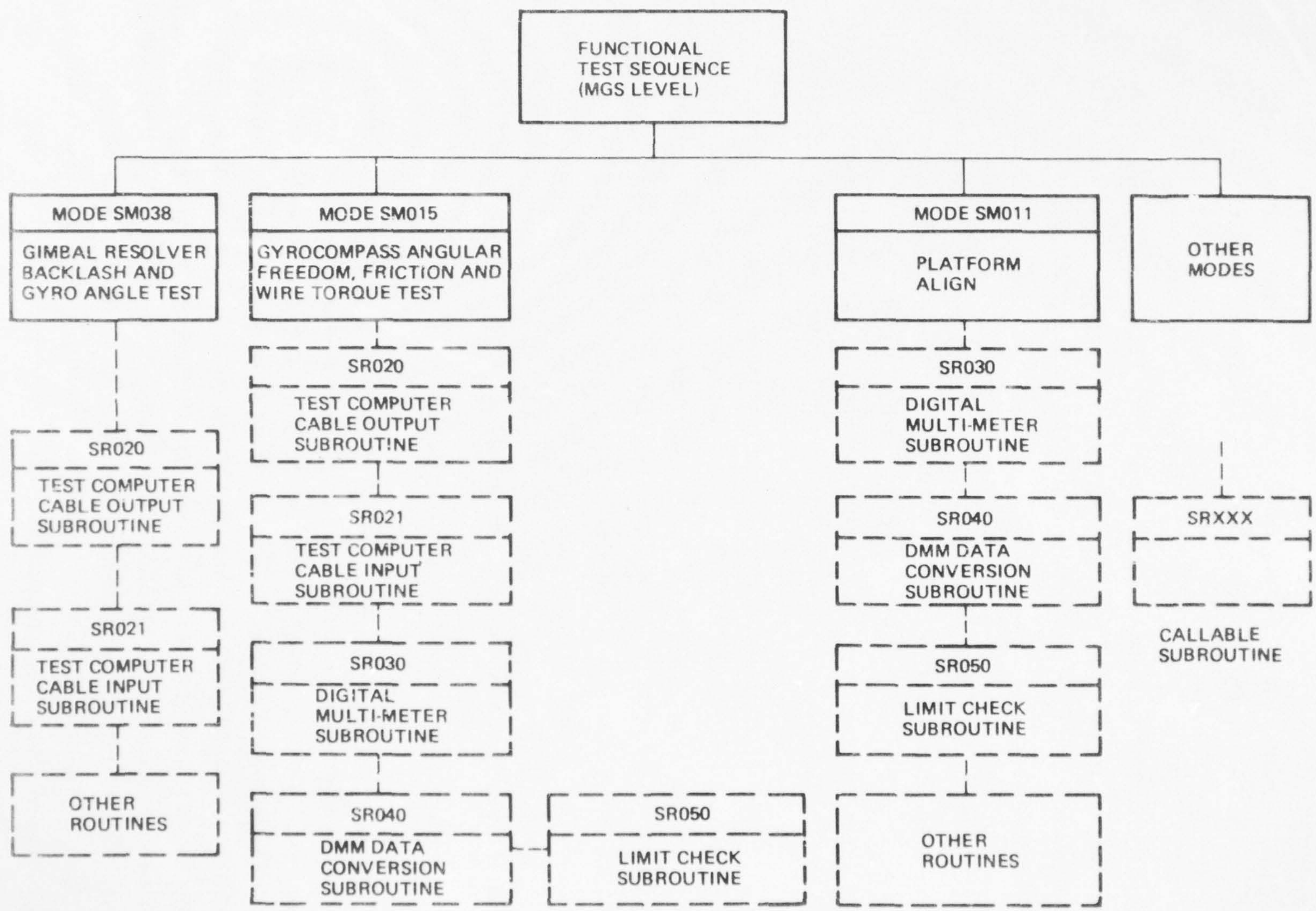

Figure 1. Sequence, Mode, Subroutine Relationship

equipment mode selection, limit checks, slewing, etc, are programmed as subroutines callable by the test modes. Figure 1 illustrates how these subroutines are repeatedly used along with other subroutines to form different test modes. Programming at the subroutine level permits one to easily make corrections, to incorporate diagnostics and to respond to hardware and operational software design changes with a new or revised program. Revising a single subroutine shared by many modes is obviously easier to accomplish than if the function is imbedded in each mode.

Each test program has a test program sequencer which is loaded into core and controls the sequencing of the test according to operator command inputs. The sequencer cycles through requested subtests or modes as follows: the first subtest or mode is loaded into core memory, executed, and then released upon successful completion; the second subtest or mode is loaded into core, executed, and then released upon successful completion; all subsequent subtests or modes are handled similarly.

The operator may request the sequencer to automatically execute an entire sequence, a specific mode, or a stack of eight modes to be executed as a group. The sequencer will verify that all prerequisites for each selected mode have been executed. If all prerequisites have not been met, then the program sequencer will cause the execution of those modes which will satisfy these prerequisites and then execute the selected mode.

The advantages of modularized functional test software for the Minuteman III test operation was demonstrated in the creation of the MALVIR program for the depot.

MALVIR PROGRAM OBJECTIVES AND DEVELOPMENT

The goal of the MALVIR effort for the depot was to provide an essentially automatic means of isolating the majority of MGS failures in an optimal manner in terms of time and manpower required. For those failures not easily isolated or of an intermittent nature, automated routines were provided as tools to aid depot personnel in the fault isolation process.

Prior to development of MALVIR programs, Minuteman III DMGE and functional test software had been delivered to NAFS depot and became operational on 1 July 1970. Development of the MALVIR programs was accomplished in two phases. Phase One was completed on 24 November 1971, and Phase Two was completed on 31 July 1972.

MALVIR Development - Phase One

The purpose of a Phase I MALVIR Program was to provide an early diagnostic capability to the depot utilizing manually selected test modes to isolate faults. Automatic fault isolation procedures were supplied at a later date in Phase II MALVIR. Figure 2 is a flow chart of Phase I MALVIR operations.

Phase I MALVIR program supplied information and options a skilled technician could utilize to more efficiently isolate the cause of specific NO-GO's. Test routines were built to aid the investigation of elusive or intermittent failures. The data and options provided in MALVIR Phase I were used in building Phase II test sequences which were designed to isolate the cause of a NO-GO to a specific component.

An example of the use of existing functional test modes to build diagnostic sequences for Phase I and Phase II MALVIR is shown in Figure 3. As shown in Figure 3, Phase I, primarily, consisted of a manually selected sequence of functional test modes plus some Phase I diagnostics to provide the operator with additional information regarding the failure (in the example shown, a platform slew timer diagnostic).

MALVIR Development - Phase Two

MALVIR programs (Phase II) are divided into two sections. Section one is for the isolation of faults indicated by NO-GO's received during depot functional testing. Section two is for the isolation and verification of the field indicated faults. The diagnosis of field faults and depot faults are closely related since almost all field faults can be traced to depot NO-GO's. The major difference between these two sections is that for field faults, it may be necessary for the technician to enter data to the test computer from the field failure report if the data is not retrievable from the AVE computer. Otherwise, the field fault analysis starts by determining the exact failure which occurred in the field from analysis of the data stored in the AVE computer (D37D). A flow chart of the Phase II MALVIR operations is shown in Figure 4.

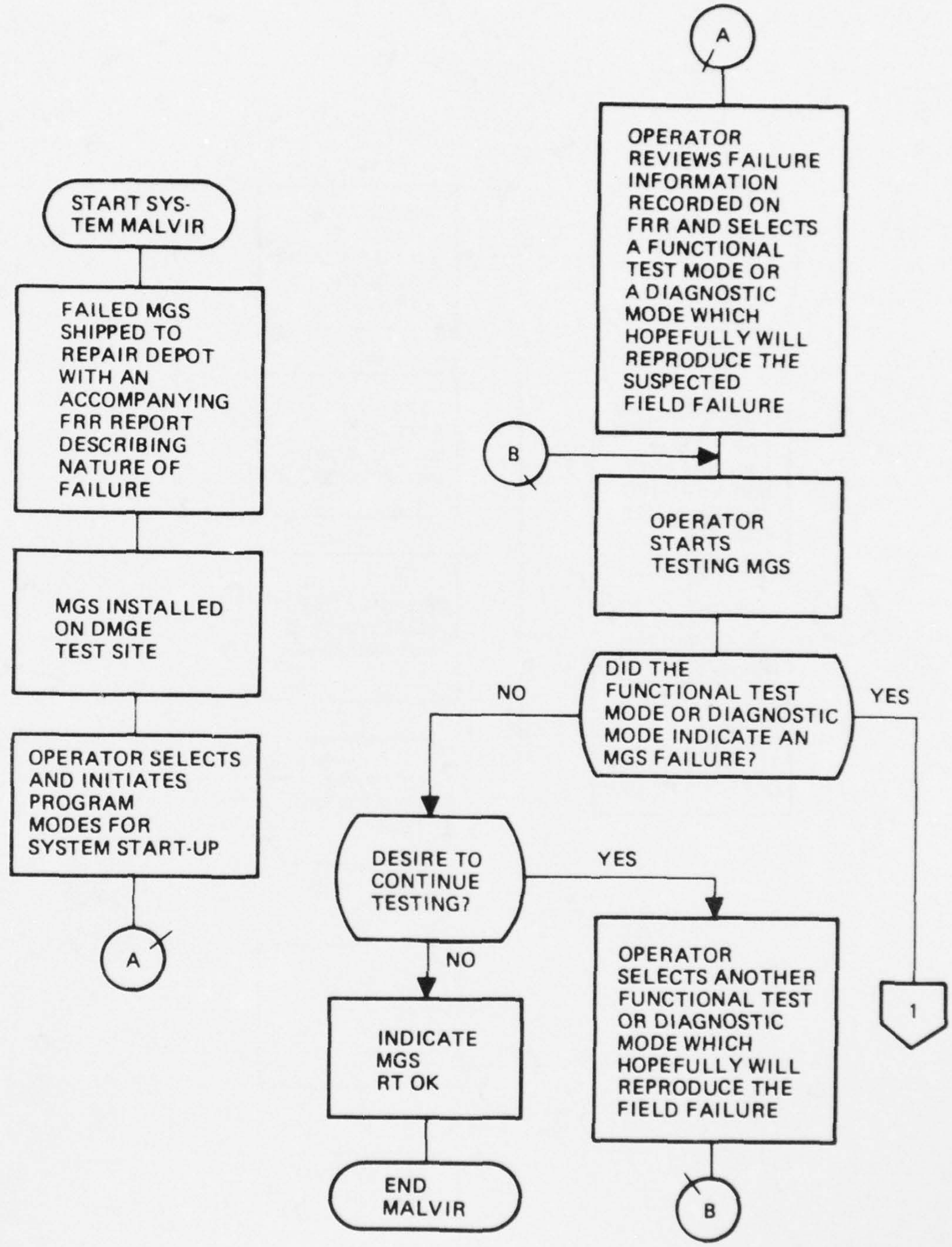

Figure 2. Flow Chart of MALVIR Operations Phase I (Sheet 1 of 2)

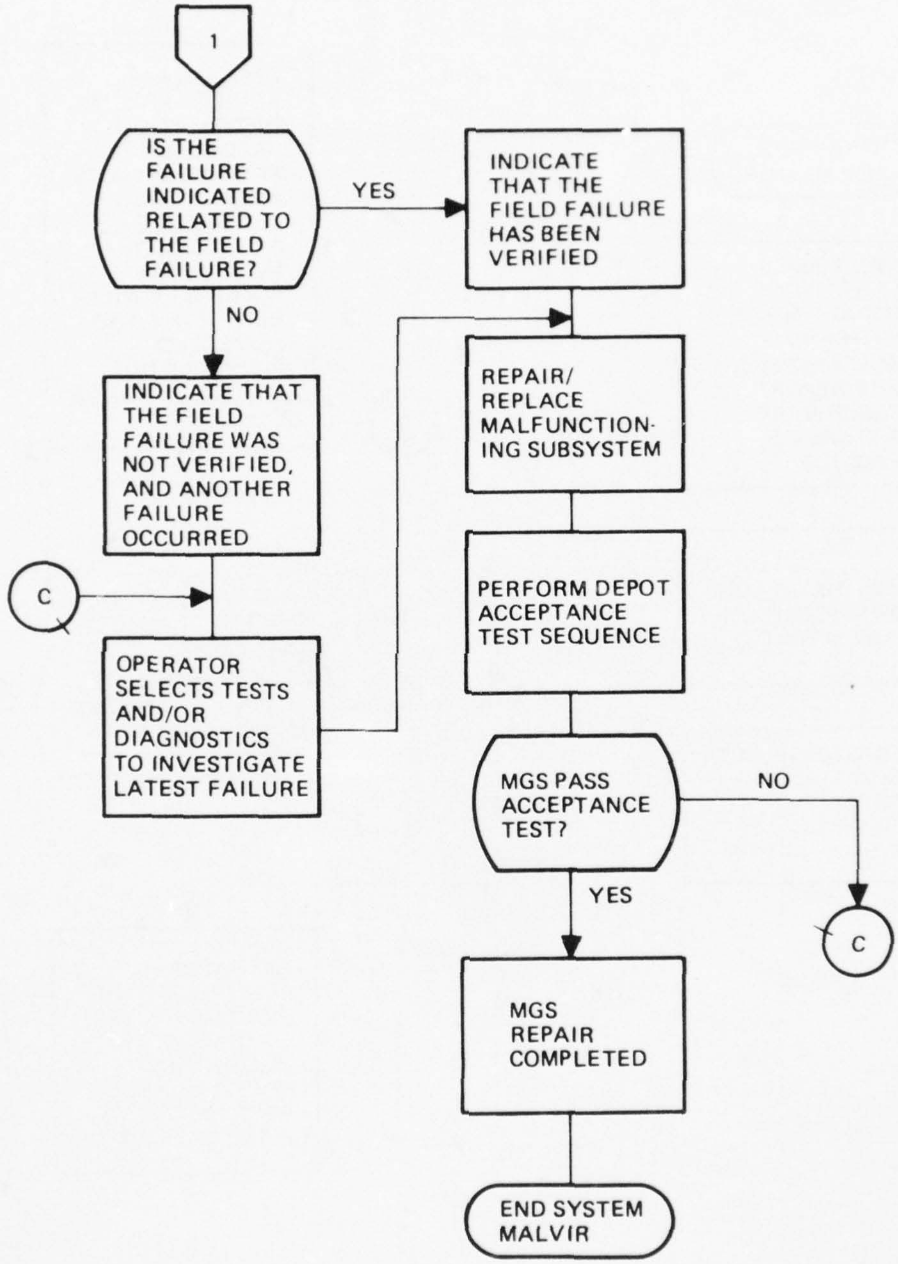

Figure 2. Flow Chart of MALVIR Operations Phase I (Sheet 2 of 2)

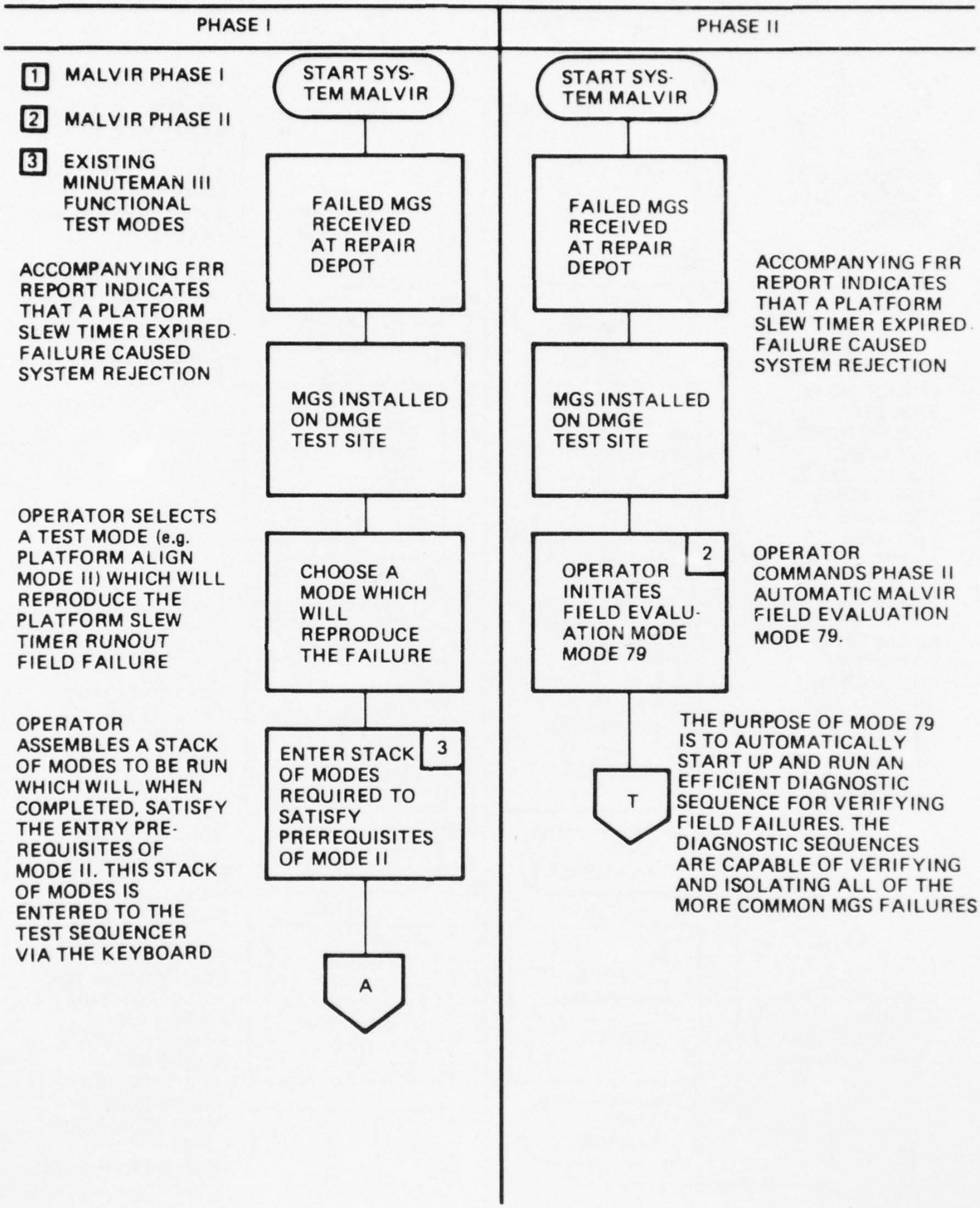

Figure 3. Comparison of Phase I and Phase II MALVIR Sequences For Verifying A Platform Slew Timer Runout Field Failure (Sheet 1 of 5)

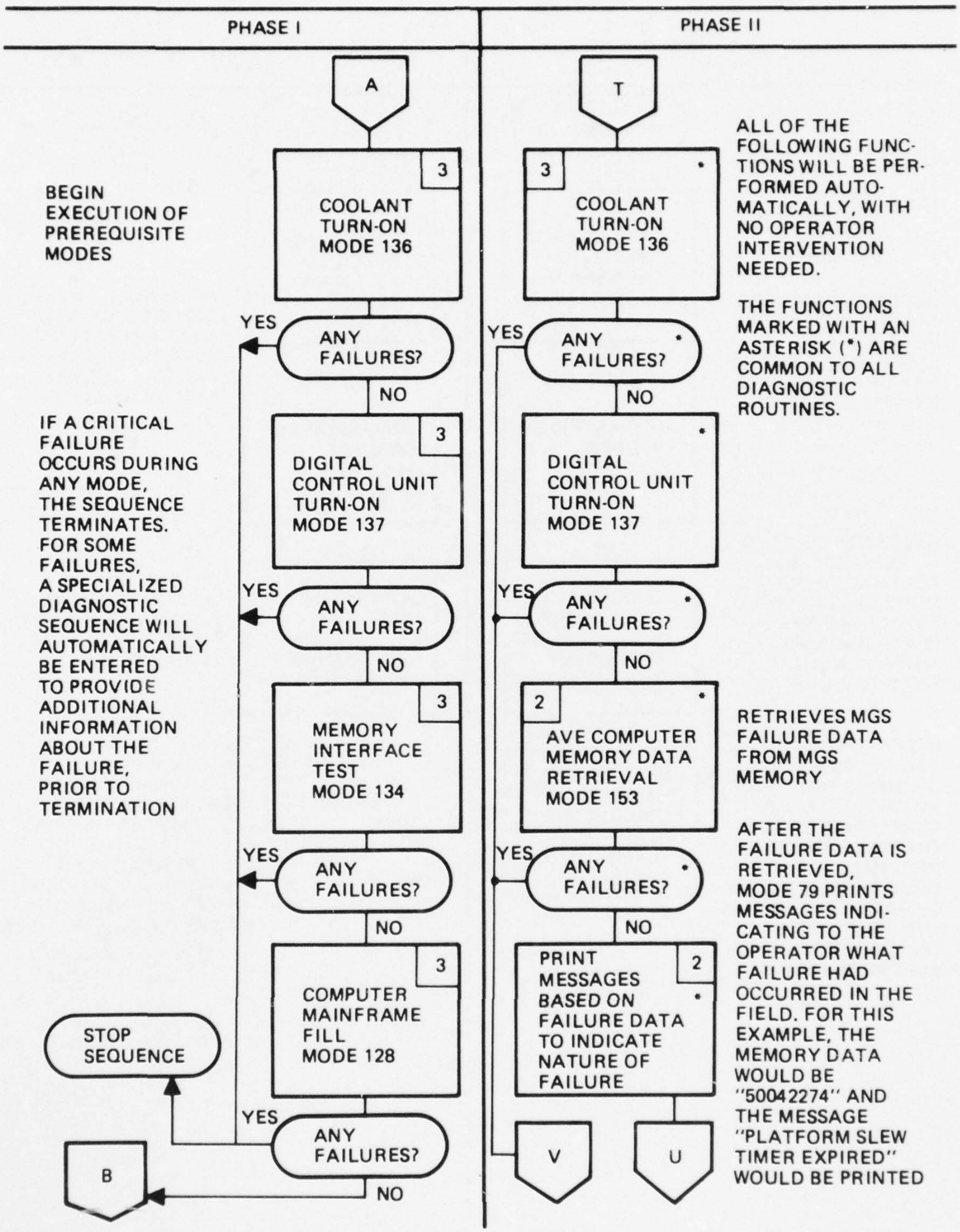

Figure 3. Comparison of Phase I and Phase II MALVIR Sequences For Verifying A Platform Slew Timer Runout Field Failure (Sheet 2 of 5)

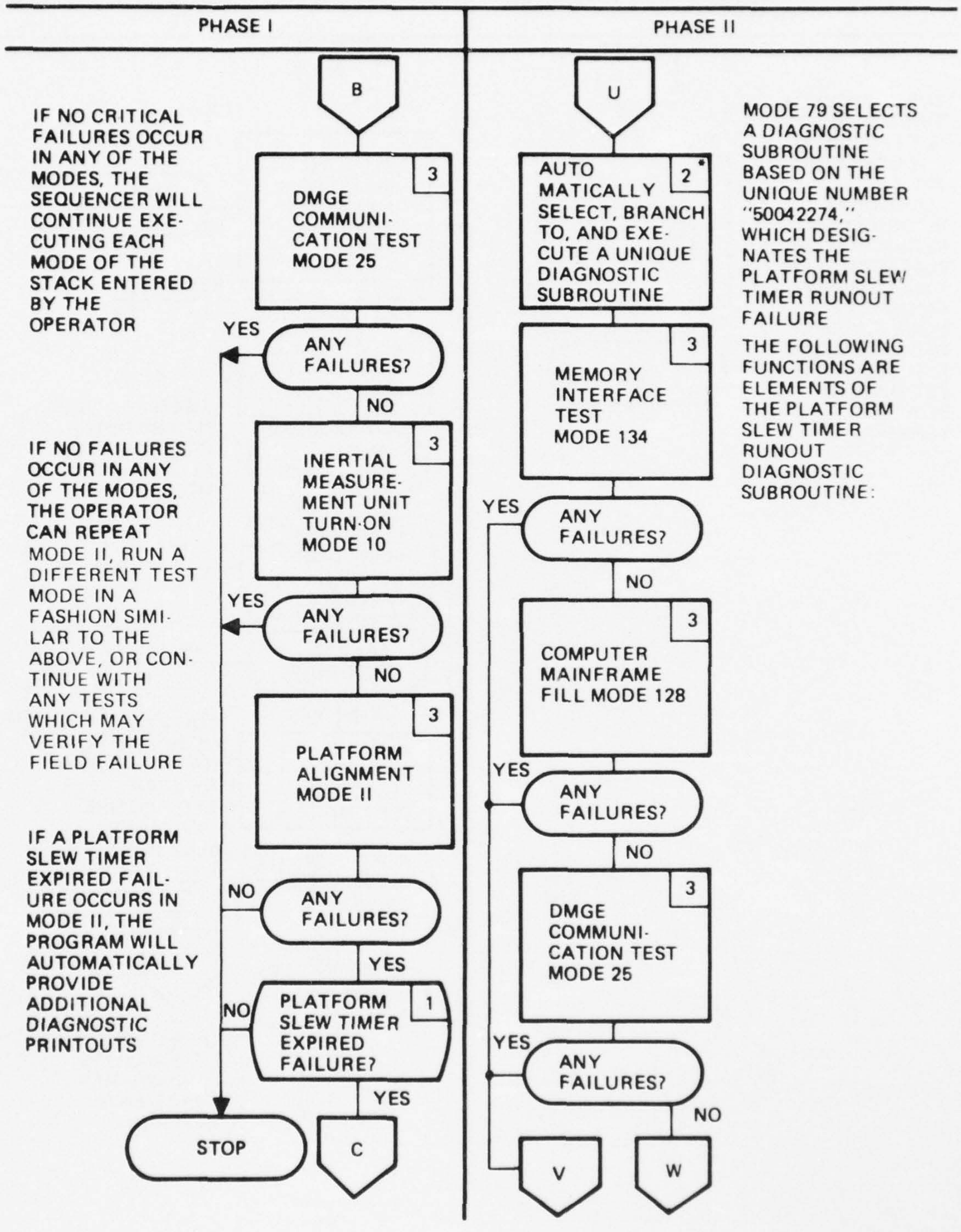

Figure 3. Comparison of Phase I and Phase II MALVIR Sequences For Verifying A Platform Slew Timer Runout Field Failure (Sheet 3 of 5)

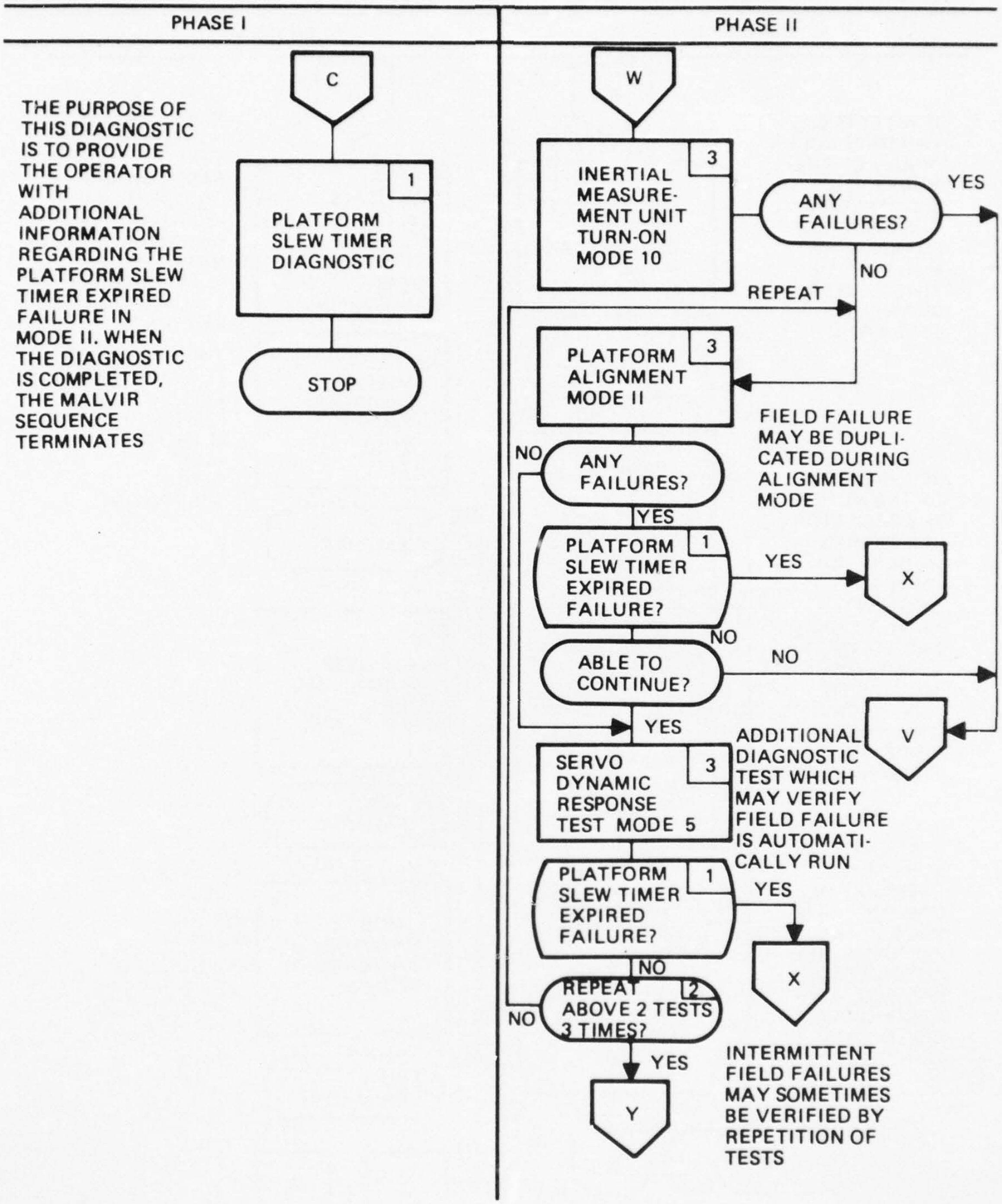

Figure 3. Comparison of Phase I and Phase II MALVIR Sequences for Verifying a Platform Slew Timer Runout Field Failure (Sheet 4 of 5)

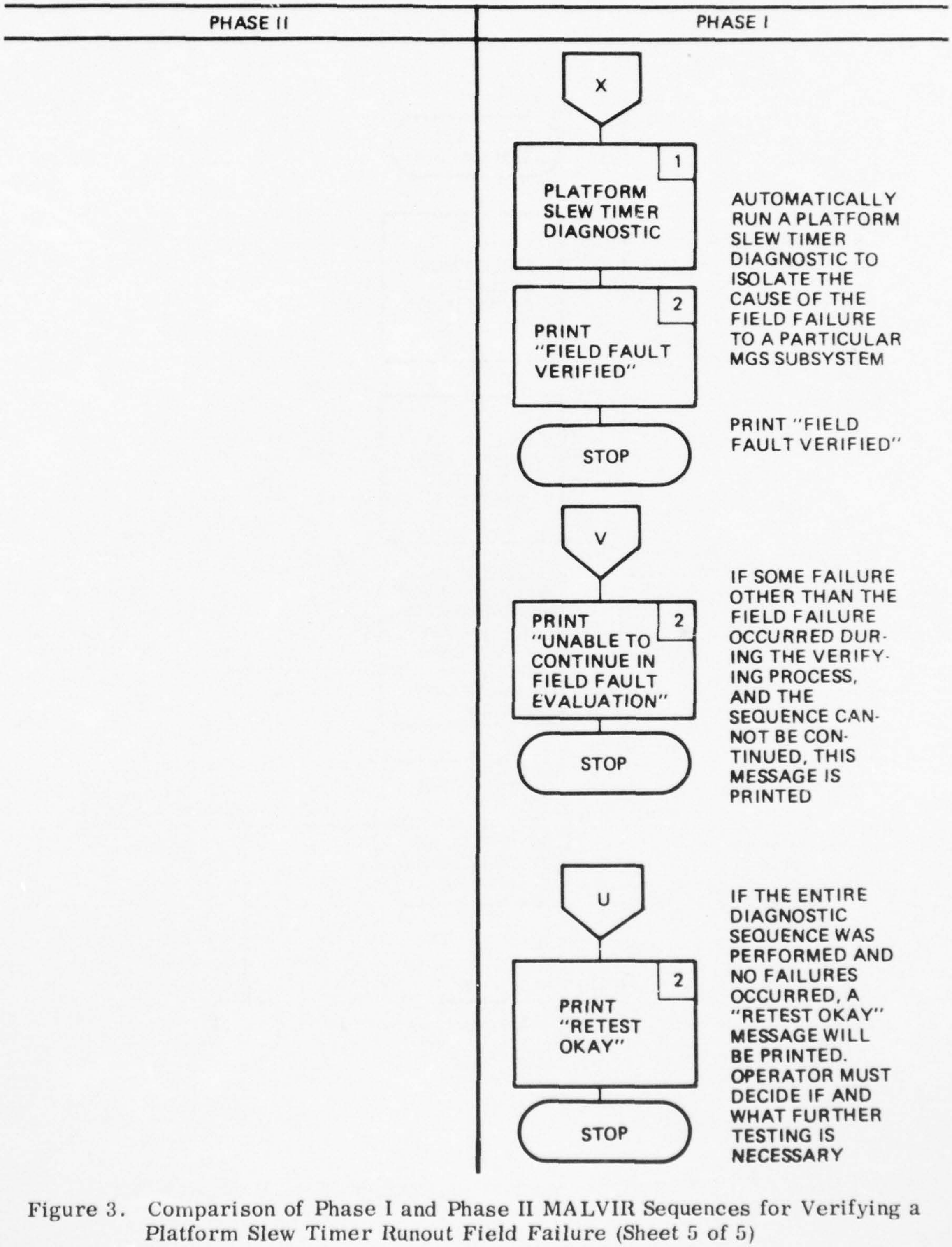

Figure 3. Comparison of Phase I and Phase II MALVIR Sequences for Verifying a Platform Slew Timer Runout Field Failure (Sheet 5 of 5)

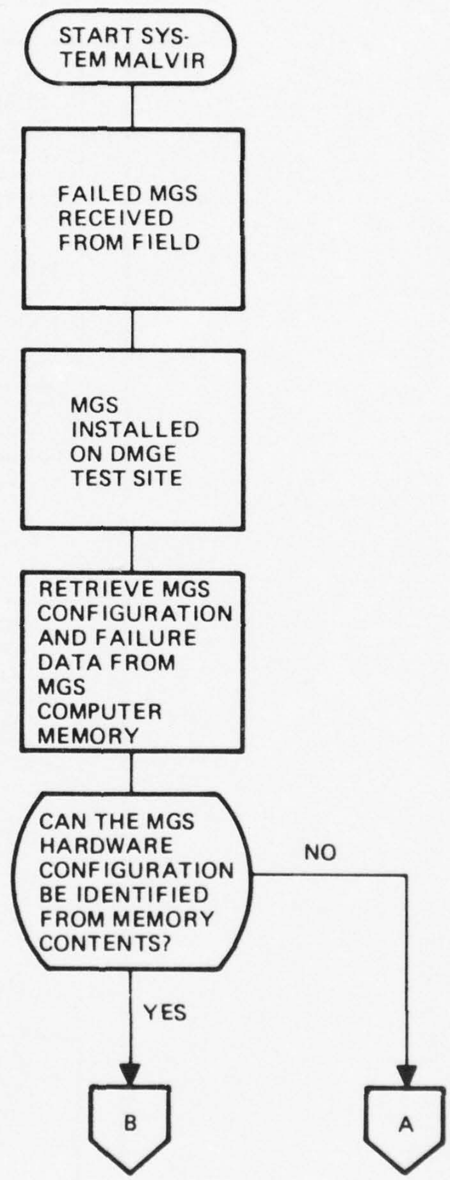

Figure 4. Flow Chart for MALVIR Operations Phase II (Sheet 1 of 3)

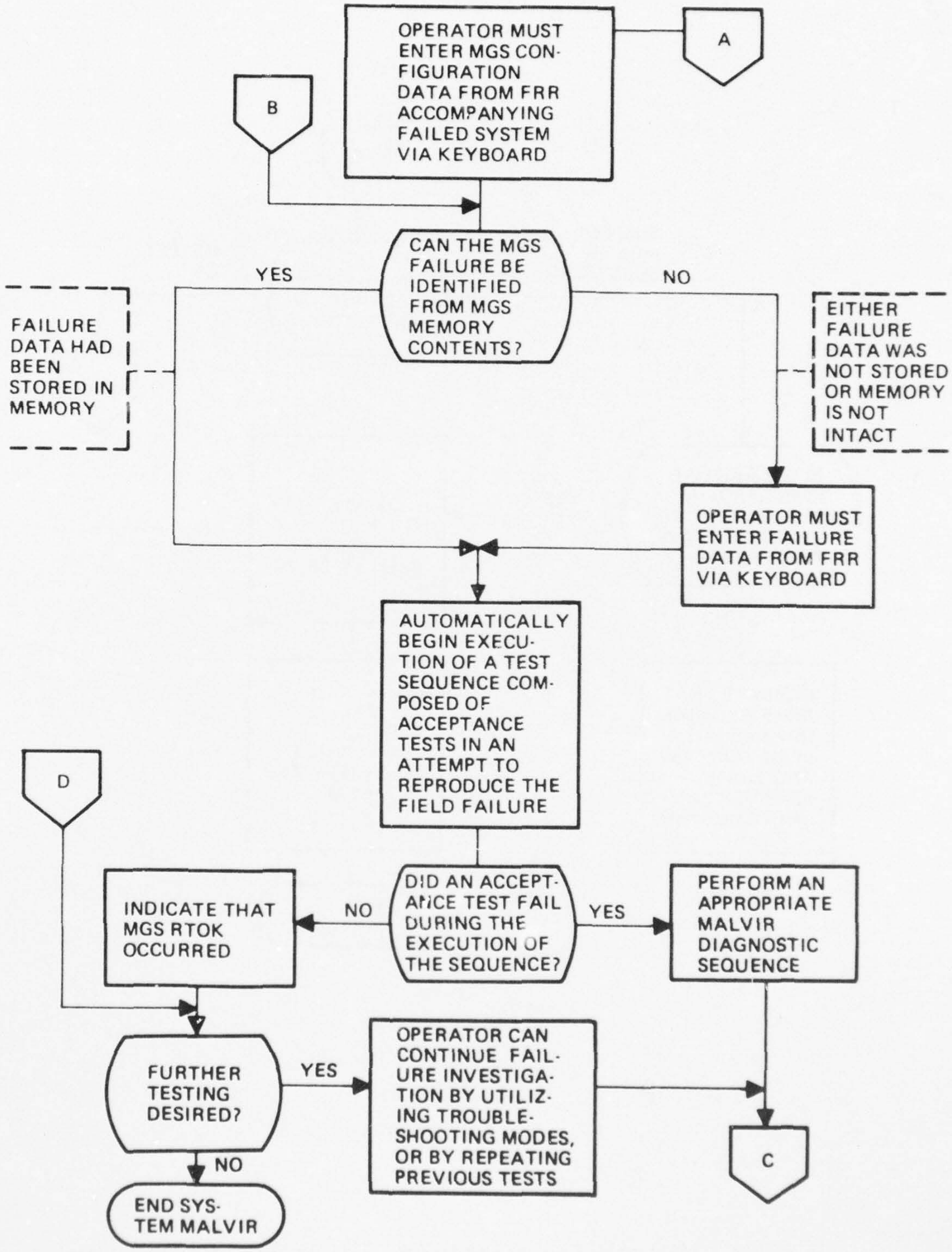

Figure 4. Flow Chart for MALVIR Operations Phase II (Sheet 2 of 3)

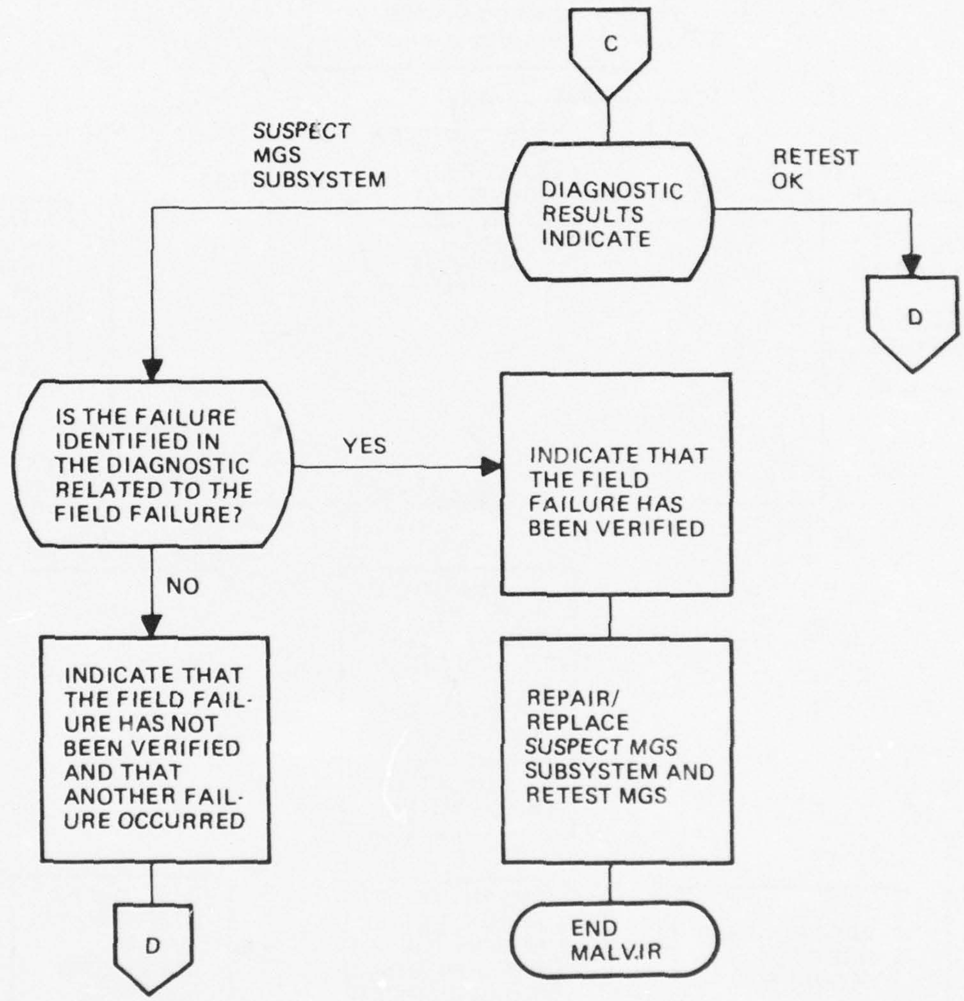

Figure 4. Flow Chart for MALVIR Operations Phase II (Sheet 3 of 3)

The requirements for Automatic AVE fault isolation were keyed to reproduction of the event sequence which produced the depot functional test NO-GO or the field fault indication. A diagnostic mode is provided for each depot AVE NO-GO (or group of NO-GO's) and each field fault indicator (or group of indicators). These modes consist of a series of decision making steps, and the results of each step determine what the next step in the series will be. These modes were developed using a building block theory of fault isolation. That is to say, that each subsequent step is based on the premise that the previous steps produced reliable results.

As shown in Figure 3, Phase II MALVIR automated the diagnostic process by means of the Field Evaluation Mode (79) and the AVE Computer Memory Data Retrieval Mode (153) plus additional diagnostic routines. Mode 153 was used to retrieve field failure data from the computer memory and Mode 79 selects a diagnostic sequence based on the failure data. Existing functional test modes were utilized to reproduce the field failures.

In the example shown in Figure 3 of a Slew Timer Runout failure, the linkage of existing functional test modes coupled with the retention of diagnostic data in the AVE computer and the test computer created the required diagnostic routine. For Phase I MALVIR the operator selected and entered, via the keyboard, the required sequence of modes to isolate the failure. Failure messages provided instructions to the operator. Phase II utilized the automatic capabilities provided by Modes 79 and 153 to select the correct sequence. Isolation of other field faults were handled in a similar manner.

CONCLUSION

Modularization of functional test software coupled with common Automatic Test Equipment (ATE) for production and depot testing provides an efficient method of meeting present and future functional and diagnostic test requirements.

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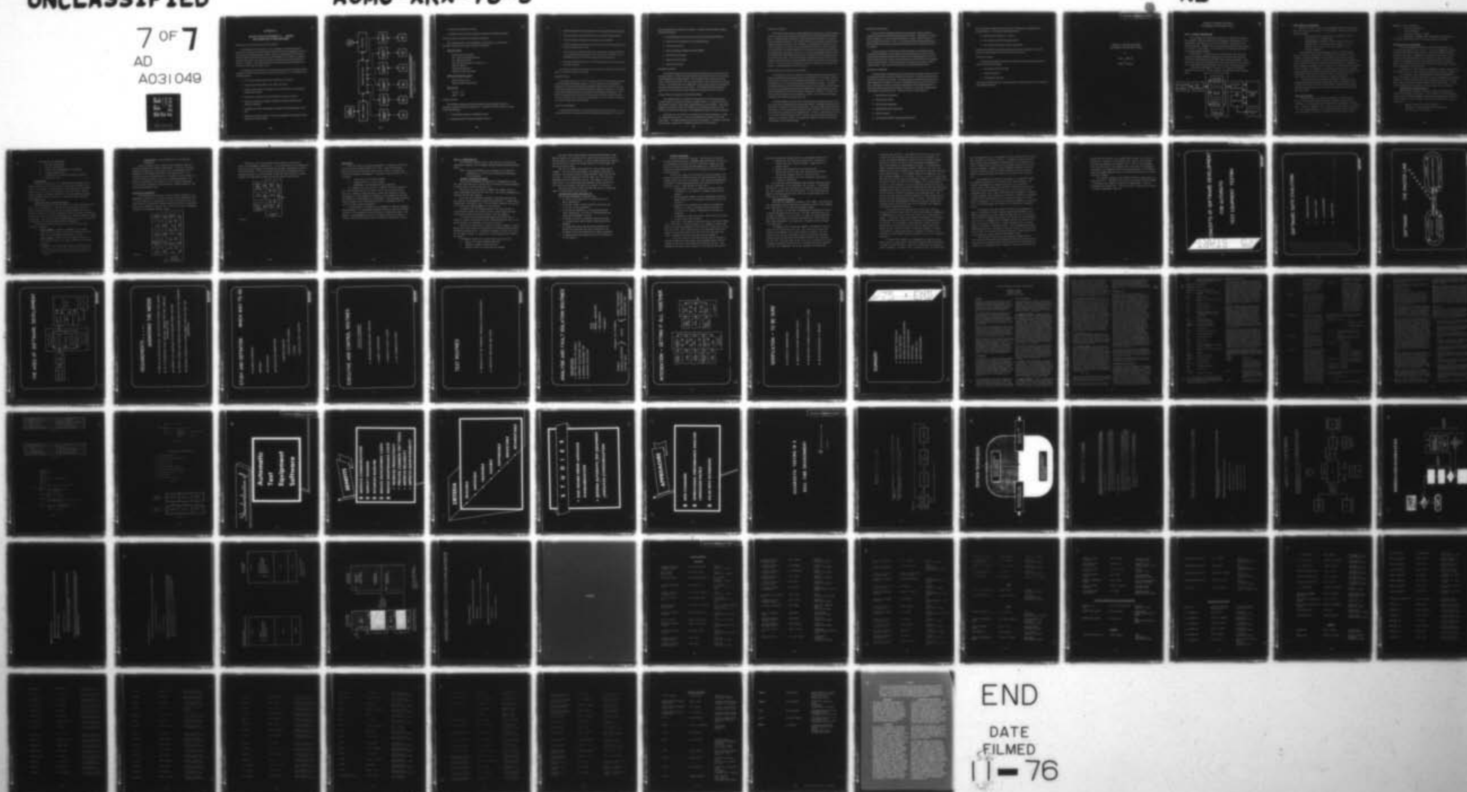

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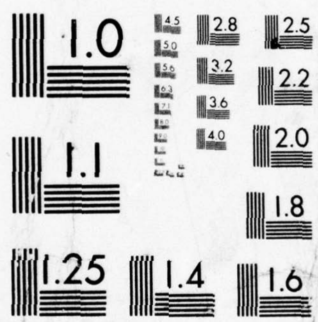


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX A

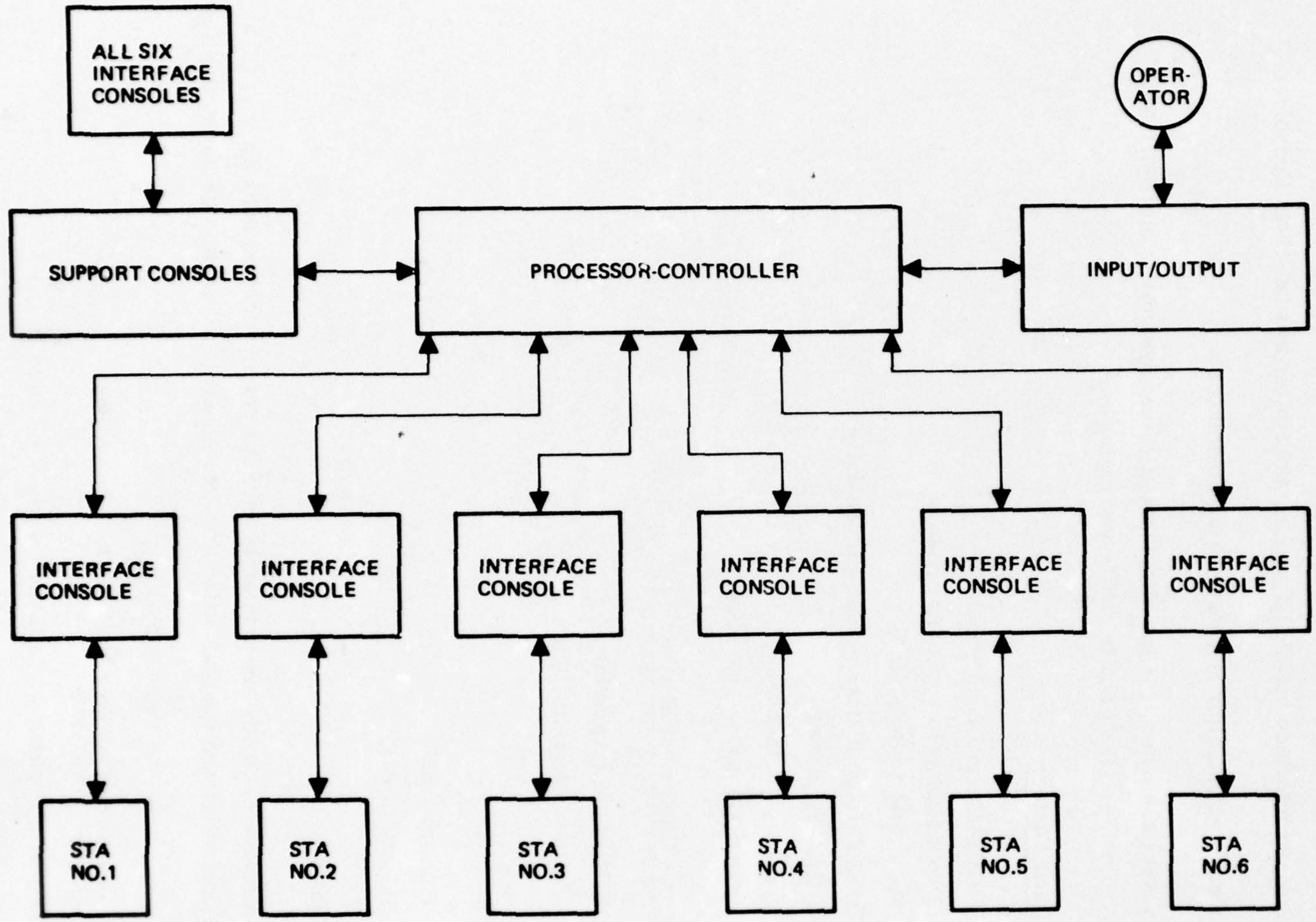
DESCRIPTION OF MINUTEMAN III HARDWARE AND OPERATING SYSTEM HARDWARE

DESCRIPTION OF MINUTEMAN III TEST SYSTEM

The Minuteman III Test System provides an effective automated method of performing both factory functional testing and depot functional and diagnostic testing of the Minuteman III Missile Guidance System (MGS) and subsystems [Gyro Stabilized Platform (GSP) and Missile Guidance Set Control (MGSC)]. The Factory Acceptance testing is performed in the course of equipment sell-off at the Autonetics facility in Anaheim, California. The depot functional and diagnostic testing is operated by the Air Force at their depot in Newark, Ohio.

The Minuteman III Test System is a time-shared test complex utilizing a central computer to control and monitor test operations (see Figure A-1). The system has the following features:

1. A test complex which concurrently controls six test stations.
2. The test station types (MGS, GSP, MGSC) are mixed.
3. Testing at each station is independent of and asynchronous to the testing of all other test stations.
4. Each station is ensured of time allocation for real-time functions.
5. Computer resources are equally available and sharable among all test stations in operation.
6. A single copy of each test program is retained in relocatable format on the disk.
7. Programs in core are shared. (One copy is capable of servicing all six test stations are the same time.)



ALL SIX STATIONS MAY BE PERFORMING SIMILAR OPERATIONS
OR THEY MAY EACH BE CONTROLLING UNIQUE PROCESSES

Figure A-1. Six-Station Test Complex

8. Support test equipment is shared.

9. Standard interface between Program-Controller and Interface Consoles.

Central Processor-Controller and Peripheral Equipment

The central computer, for the Minuteman III Test System, is an IBM 1800 Processor-Controller (P-C) and is configured as follows:

Depot and Factory

IBM 1442 card read/punch
Two - IBM 1816 keyboard printers
Six - IBM 1053 printers
IBM 2310 disk storage unit - three drives
IBM 1627 plotter
Tally mylar tape punch
Digitronic mylar tape reader

Additional Equipment at Depot

IBM 1443 line printer
Western Electric 201B modem

Memory Size

Factory - 32K
Depot - 64K

Interface Consoles

The interface consoles are primarily used for communication between the Processor-Controller and the unit under test. In general, all of the interface consoles provide the following:

1. 28 vdc primary power and monitoring circuits

2. Coolant and power control and interlock circuits

3. Digital multimeter for measurement of AVE and interface console signals.

4. Test point selector for selecting any AVE or interface console signal.

5. Limited signal conditioning for such items as peak detection.

6. Central switching which provides loads for the AVE, stimuli application and interface console master reset.

7. Process interrupts which are utilized by the interface console to notify the P-C of problems detrimental to the AVE, such as loss of coolant, or the completion of items such as digital multimeter measurements.

8. Electrical isolation between the P-C and the interface consoles using input and output isolators.

In addition to the above common items, the interface consoles provide functions which are unique to each level of testing.

Support Consoles

Two support consoles are used in conjunction with the above interface consoles to test Minuteman III Guidance Systems. The two consoles, the Central Power Console (CPC) and the Self Alignment Technique Control Console (SATCC) provide those unique functions which were considered cost effective to combine, or have low usage and the capability could not be justified on an individual station basis. The SATCC basically provides control of the optics utilized for the azimuth reference. The CPC provides a servo analyzer, timing signals, gyro start voltages, nonprimary AVE power sources and a timer/counter.

EXECUTIVE PROGRAM

The Executive Program is the operating system of each test complex. It controls and allocates the computer resources and the support consoles in accordance

with the requests of the different test stations. Features of the Executive Program include the following:

1. Scheduling algorithm with both real-time and time-sharing attributes.

2. Dynamic memory allocation with a paging technique.

3. Nonprocess functions.

4. Special message processing and data handling.

5. Input/Output processing.

6. Operator communication.

7. Interrupt processing.

Scheduling Algorithm

The scheduling algorithm of the Test System includes both real-time and time-sharing attributes. The most constringent time-critical element exists in the testing of the Minuteman III Guidance System. The Guidance System requires a 60 msec servo control servicing rate. This servicing, however, may be performed in 6 msec or less. It was determined that an additional 4 msec would be sufficient to handle the non-time-critical functions of a test system. The Schedular was thus designed to operate with 10 msec intervals and to allocate time among the six test stations.

Dynamic Memory Allocation with Sharable Routines

The resident Executive occupies the low portion of core and contains those routines which are required at all times to support testing. To minimize the size of the resident Executive, most major routines utilize an overlay scheme. The overlay programs are stored on disk in an absolute core image format and may be read directly into memory for execution, thus bypassing the program relocation operation.

That portion of core which is not occupied by the resident Executive is called the "Paged Subroutine Area." This area is subdivided into blocks of 256 words called pages. All paged programs are written to be sharable. A program is sharable when one copy in paged core is capable of serving all six test stations.

Nonprocess Functions

The Minuteman III Executive Online Nonprocess capability is an adjunct function which serves as a programming and maintenance aid to the total Minuteman III software. It consists of two assemblers, a disk file management function, a message library maintenance function, a set of utility programs and a monitor program which interfaces with the Executive. One assembler, the Paging Macro Assembler, provides the capability of modifying and reassembling both Executive and test programs for the IBM 1800. The other assembler, AJAX, provides the capability of modifying and reassembling test programs for the D37. The disk management function provides the capabilities for updating the disk file of test programs and for maintaining control of the status of the disk. The message library maintenance function may be used to change individual messages or load/reload the entire message library (see following section). There are six utility programs to assist the programmer in patching, displaying, or protecting areas of the disk or core.

Special Message Processing and Data Handling

The Executive provides the capability of storing prototype messages with data format specifications into message libraries on the IBM 1810. Messages are stored successively in a library and are assigned unique sequence numbers. This number is subsequently used in a test station program to reference the message. A specific test station type can access only messages in its own libraries (thus a GSP test station may not access a message contained in the MGS library). Storing messages in this manner eliminates the necessity of having to define them internally in a routine and thus reduces the amount of core required by a routine. It also makes all messages available to all routines of the same test type.

The Data Handler will accept from a Periodic Program requests to open a data file, enter data into that data file and close that data file. All other functions must be performed as a sequential non-time-critical task. The Data Handler also controls the transmission of data via the modem between the IBM 1800 and a remote SEL computer (the Central Data Acquisition and Analysis System - CDAAS). Upon the close of a data file, the Data Handler analyzes all data in the file, selects that data which has been flagged as CDAAS data, places it in transmission tables and verifies the successful transmission to the CDAAS computer.

Operator Communications

The two IBM 1816 Keyboard/Printers are the primary means by which an operator communicates with the Minuteman III Test System. The operator communicates to stations 1, 2, and 3 through the IBM 1816 - Group 1, and to stations 4, 5, and 6 through the IBM 1816 - Group 2. If an IBM 1816 fails during test operations, then the software automatically permits the other IBM 1816 to communicate with all six stations.

The main operator communication options available to the operator include station startup/shutdown, control input to a test station program, and data control. Those options whose execution may be critical such as station shutdown or control input are executed in the overlay areas (200 words for each IBM 1816) of the Operator Communications section. Those options whose execution is not so urgent such as station startup or data retrieval are executed in the Paged Subroutine Area.

Input/Output Processing

The Input/Output Processing section of the Executive program controls all of the I/O peripheral devices associated with the test complex. The devices except for the modem are divided into two groups. The first group includes those devices which are shared among all six stations, but which are allocated for use by only one station at a time. This group includes those devices whose Input/Output would be garbled if it were being used by more than one station at a time (e.g., one station reading cards, while another was punching cards). The seven devices of this group are:

1. IBM 1442 card read/punch.
2. IBM 1443 line printer.
3. TALLY mylar tape punch.
4. DIGITRONICS mylar tape reader.
5. IBM 1627 plotter.
6. The two IBM 1816/1053 (Keyboard portion only).

The second group includes those devices whose I/O requests are handled using a queuing technique. The devices of this group include:

1. IBM 2310 disk storage unit - 3 drives.

2. The two IBM 1816/1053 keyboard/printers.

3. The six IBM 1053 printers (one for each station).

The queuing technique is a scheme whereby successive I/O requests for a specific device are chained together in the order of their occurrence.

Interrupt Processing

The Interrupt Handler of the Executive program is designed to handle the three IBM 1800 basic interrupt types.

1. Input/Output Device Interrupts.

2. Process Interrupts.

3. Programmed Interrupts.

The Interrupt Handler provides a means whereby a response routine may be associated with a specific interrupt.

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CONCEPTS OF SOFTWARE DEVELOPMENT FOR AUTOMATIC TEST EQUIPMENT TESTING

BY

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&
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CONCEPTS OF SOFTWARE DEVELOPMENT
FOR AUTOMATIC TEST EQUIPMENT TESTING

PART I - GENERAL CONSIDERATIONS

The concepts for developing software to be applied to automatic test equipment (ATE) are based on sound judgment, understanding of the requirements, and familiarity with the functional flexibility of the devices involved. Although the term software has generally been applied to a variety of data types, it is treated in this writing exclusively as computer program elements.

Evolution of a software suite for ATE requires definition and creation of program coding, program aids, and related data essential to defining and producing the Automatic Test Equipment programs. Software is the paper that describes and enables the processes of converting the testing concepts and philosophy into an actual operating program.

Software is developed as a result of a logical multi-phase sequence of activities. Figure 1 depicts the process in block diagram form.

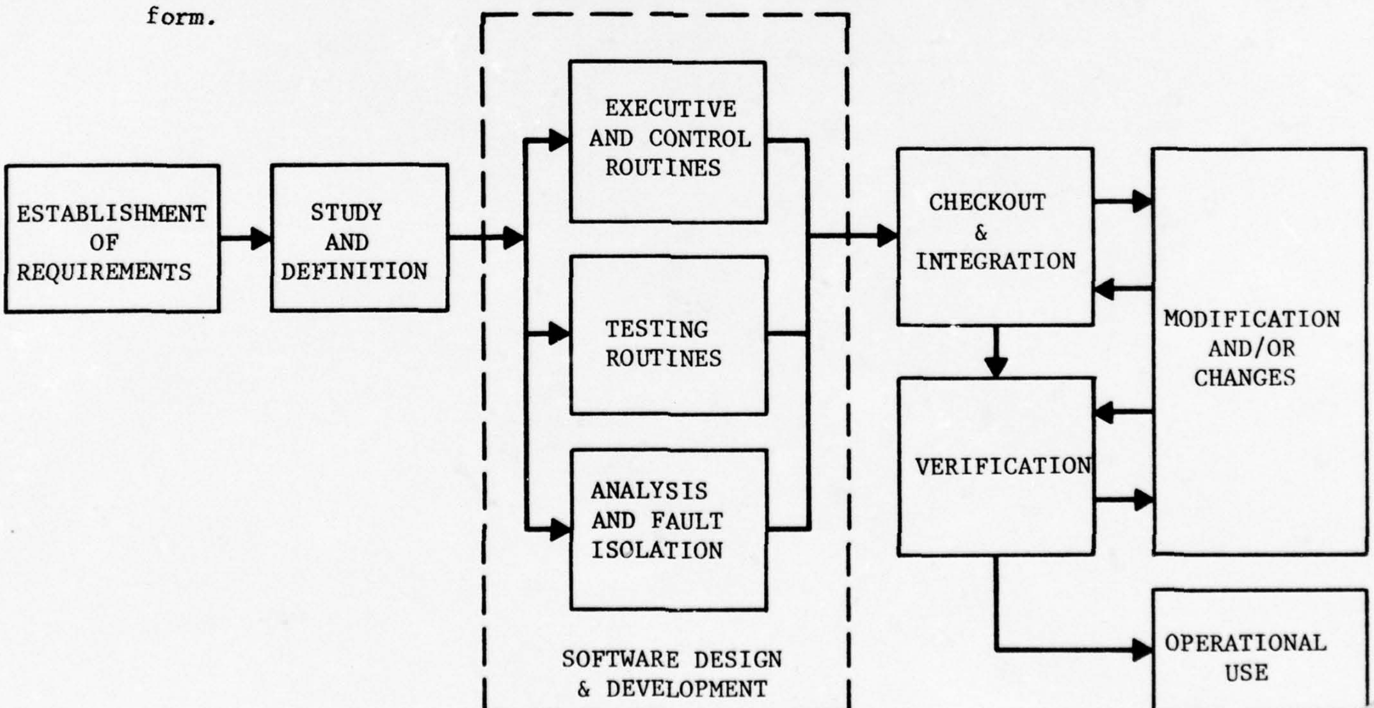

Figure 1

ESTABLISHMENT OF REQUIREMENTS

The initial step in ATE software development defines the requirements and goals of the programs to be developed. These can be generally stated as follows:

- Verification, with a high level of confidence, that the unit under test, is operational.
- Accomplishment of effective fault isolation of an inoperative unit to the lowest desired level, i.e., subassembly, card, group of related components, or individual component.

The anticipated testing philosophy should be pre-determined since it can have a great deal of influence on the design of the ATE involved. Detailed knowledge of the system to be tested as well as the ATE characteristics serve to define the capabilities and limitations under which the software can and will operate effectively. Automatic Test Equipment philosophy plays a primary role in the end result complexity of the software. For example, the software required to test an entire system simultaneously, while simulating external interfaces, would differ considerably from software required to test a system, one unit at a time, with both internal and external interfaces simulated.

In addition to the requirement for explicit definition, the software being developed must be reasonable from a standpoint of constraints imposed by the system and/or the ATE. These factors must be identified accurately prior to the study and definition phase of software development.

STUDY AND DEFINITION

The second phase of software development for ATE requires a study of the various software approaches, methods, and techniques available for attaining the goals identified in requirement establishment. From this "shopping list" a selection is made which is considered to be the optimum approach, and a detailed "structure and composition" software package is defined. This phase can involve three software

domains or sets of functions:

- o Executive and Control
- o Testing Routines
- o Analysis and Fault Isolation

It is important to remember that even though these domains can be defined individually, their interaction cannot be avoided.

SOFTWARE DESIGN AND DEVELOPMENT

With the philosophy of testing and definitions complete, the software design phase can be started. It may be economically feasible to develop the executive/control, test, and analysis/fault isolation routines concurrently. Regardless of technique, this effort will include detailed code generation and assembly of various instructions required to implement a series of well defined routines. Software should also be designed to facilitate additions and/or changes required due to improvements or corrections.

In addition to these software programming functions, documentation, and checkout aids, such as listings and flow charts, must be created.

Close software design and development supervisory management must be maintained to assure satisfaction of the "accomodation discipline" concepts. The developed routines, when integrated within the time and space frames, must not exceed the computer system limitations. In most cases allowance should be made for a certain percentage of growth.

Executive and Control Routines

The executive and control routines provide the framework for establishing testing requirements to meet automatic testing objectives. These routines provide management direction and communication supervision for the overall software package. The executive and control routines provide for:

- o Control instructions from the operator
- o Updating of status displays indicating progress and results of various tests.

- o Options for test sequencing:
  - o Run test sequentially
  - o Run test individually
  - o Iterate test individually or sequentially
  - o Internal communication
  - o Coordination of collective software functions relative to time.

Test Routines

Ideally, the individual test programs should be modular, this improves their utility for application to more than one area of the overall test program. A prime objective in structuring an individual test routine is to limit the functional area to be tested. With a tightly bounded test domain, failure of a test pinpoints the problem area and provides fault isolation to a lower level than with gross testing approaches.

Analysis and Fault Isolation Routines

Many approaches can be used to realize the fault isolation requirements of a test program set. The versatility and character of the specific selection may well depnd on; how many parameters are to be tested in a given unit of time, projected levels of training of operators, the time available for software development, and possibly budget or funding limitations. One or more of these considerations can serve as constraints to optimization of ATE associated software development.

The fault isolation process may fall in one or more of the following categories:

- o Manual (INBRED) - Using his knowledge of the system under test, the operator makes fault isolation decisions based on the tests which were passed or failed.
- o Manual (AIDED) - Based on using a technical manual or fault isolation chart, the operator makes fault isolation decisions.
- o Automatic - The software makes fault isolation decisions as a function of tests failed, the manner in which they failed, and the types of tests which were passed prior to failure.

o   Semi-Automatic - Some combination of the preceding categories.

Totally automatic fault isolation and testing has some very distinct economical and technical advantages. The level of training required for operators is much lower, as is the reduced detail and complexity of the supporting technical and operation data. One extremely attractive characteristic of automation is the assurance of a uniform decision process in the fault isolation procedure. The saving of considerable time coupled with the technical advantages must be traded off against additional memory, program complexity, and associated development time.

CHECKOUT AND INTEGRATION

After design of the various routines has been checked out, as independent modules first, and then in major routine integration form, the total software unit comprised of the executive/control, test, and analysis/fault isolation must undergo checkout and further integration. These steps, depicted in Figure 2 and 3 result in a totally integrated automatic test equipment software system.

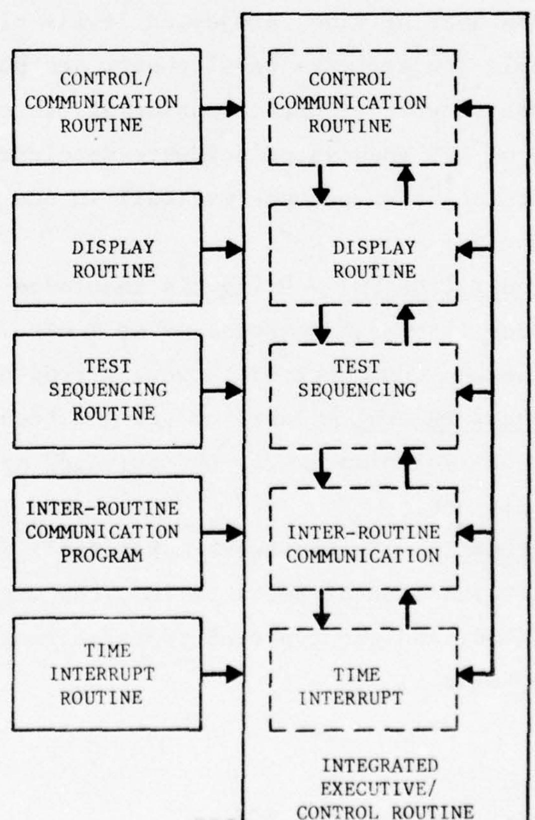

Figure 2

Completion of the ATE software system checkout, verifies all facets of the program's compatability. At various points in this checkout/integration process changes or modifications are made, rechecked and verified for functionality. The ultimate goal of this multi-step checkout and integration process is a total software system that can be applied to system hardware for operational application with or without actual faults.

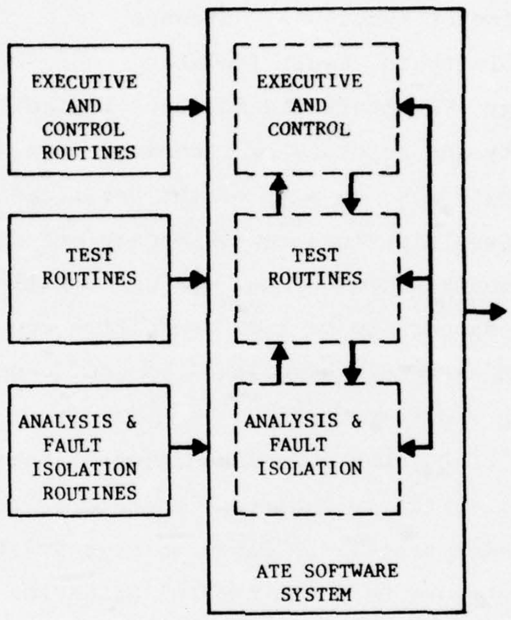

Figure 3

VERIFICATION

The final phase of software development is complete verification, proving that the software capability is real. This "Kit Proofing" exercise qualifies the software regarding its ability to satisfy the initially established requirements. Included in these exercises, are the following:

- Verification of Functional Hardware
- Program Ability to Fault Isolate
- Methodology For Analyzing Failures Logically

The compatability and accuracy of technical data which supports use of the software should also be part of the verification process. Here again, changes or modifications to these data are made to correct incongruities. These changes are checked out and verified for accuracy. The completion of what appears to be redundant, time consuming activities, yields software with an extremely high level of confidence that can fulfill the ATE testing requirements.

The development of Automatic Test Equipment is complex, demanding, and challenging. It is extremely important therefore, that the concepts applied to the development process be based on step-by-step logic. Each phase of the development must be given careful attention to provide a softwar? system which provides long term effective operational service.

PART II - OPERATIONAL USE

The concepts outlined in Part I were applied in creating the operational automatic test equipment software program described briefly herein.

TASK: Develop an Automatic Test Equipment Test Program for application to a multi-station computerized navigation training system.

Automatic Testing Requirements

The testing requirement was basically to thoroughly test each LRU, such that after test, a high level of confidence existed regarding the LRU's being a totally functional unit.

The tests were structured in a manner that readily lead to a faulty subassembly should any LRU test fail. The faulty subassembly was replaced, and the LRU retested.

Most tests were completely automatic; the exception was where this type of testing appeared economically unfeasible. In these cases, semi-automatic testing was used. The initiation, progress, and results of all tests were readily apparent to the operator.

In order to test the Converter-Storer, the test set had to electronically simulate the Control-Indicator panel, Radar Indicator, Cursor Control, and all external avionics, plus the computer.

In testing the Control-Indicator panel, the test set was required to simulate the Converter-Storer and Radar-Indicator and in testing the computer is simulated by the Converter-Storer.

The Test Set consisted of a cabinet, housing a computer, Computer Monitor Unit, Test Control and Simulator Unit, Power Distribution Panel and Power Distribution Box. A Portable Programmer Fill Unit for loading the computer memory is included, but is not physically attached to the cabinet.

The Computer Monitor Unit provided three basic functions:

- o Control of various computer operations
- o Display of computer status and data
- o Computer control of indicators and displays

The Test Control Signal Monitor electronically simulated, under computer control, all necessary input signals that may be required for the particular unit being tested. It also provided indicators, controls, and test points to furnish the system operator with the progress and results of various tests.

The test set computer was identical to the airborne digital computer. In the test set environment, the computer controlled the testing of the Converter-Storer, Control-Indicator Panel and Test Set self test. With the computer as the LRU under test, the tests were performed by the Fill and Monitor Units. The computer, under the supervision of the software and with simulated inputs from the test set, tested the Arithmetic and Control and Special I/O sections.

The Power Distribution Panel provided the means of controlling power to various parts of the test set.

Software Requirements and Objectives

The software development objectives were:

1. To verify with a high level of confidence that an LRU is operational.
2. To provide a means of fault isolating the faulty LRU to as low a level as possible.
3. To provide the capability of reiterating selected tests indefinitely, as an aid to troubleshooting and detecting intermittent failures.
4. To design all tests for automatic operation except in instances where semi-automatic operation was more feasible.
5. To design the control and operating procedures in a manner that would make the actual operation of the equipment and testing procedures as simple as possible.
6. To operate within the memory and real time constraints of the computer.

Software Development

Executive and Control Routines: The Executive and Control Routines providing the basic framework made possible the realization of established test design criteria to meet the automatic testing objectives; these routines were developed first. Individual test routines were then developed within the limitations of the executive control routines.

The Test Set executive and control routines were keyed to an external interrupt transmitted every ten milliseconds from the Test Control signal monitor to the computer. All timing and housekeeping functions to be performed periodically were executed during this interrupt routine. Some examples of these, are:

- Interrogating the test set operator interface controls to determine if the operator is communicating with the program.
- Maintaining the computer validity signal which indicates proper operation of the computer and enables various I/O functions.
- Updating various displays with either new information indicative of tests in progress and test results, or if there are no changes, redisplaying of previous information.
- Incrementing a real time counter, which would be utilized in the various test routines.

Three LRU's; the Computer, Converter-Storer, and Control Panel, were to be tested. A specific overall test, composed of many lower level test steps was designed for each LRU and the major units of the Test Set itself. Each overall LRU test was identified with a test number, and contained within that particular test were many test steps. Integral to each test step were several substeps.

It was the function of the executive and control routine to provide the operator with several options regarding which test he desired to run, and in what manner he wanted that test run. The following test options were available to the operator and could be

selected by setting the proper controls on the Computer Monitor Unit:

- o Execute the total LRU test automatically, sequentially calling each test step and sub-step, stopping only if a failure occurs.
- o Execute only one specific test step and stop.
- o Execute one specific test step, continuously repeating the process, stopping only if a failure occurs.
- o Execute one specific test step continuously even though a failure is occurring.

The executive routine performed other necessary functions which were not accomplished in the individual test routines. It determined the validity of each test requested by the operator and if an invalid test were requested, the test was rejected. It also initialized the memory at the beginning and end of each test and maintained the roll table position in memory.

Test Program Development

Each LRU test program was assigned a test number. The individual test sub-program, many of which may be required to build a test program, were identified as a test step and assigned a number.

The objective of each test subprogram (test step) was to verify a limited functional area of the LRU. The goal, where possible, was to limit the domain of each test step to a group of related components. The smaller the domain of each test step the better, should the test fail, the problem area, and related fault isolation could be defined to a lower level.

An example of this testing philosophy is the Analog to Digital section of the Converter-Storer test. The central part of the converter is time shared for all input channels, therefore, once this central part is proven, succeeding tests prove peripheral areas and functions such as individual input channel operation and accuracies. The four test steps that make up the total A to D Converter test, start as simply as possible and then build to include more and more detail, using the first elementary test as the foundation upon which the

succeeding tests are built. The objective of the first test step is to prove the time shared central part of the A to D converter. To do this the program commanded a conversion on an internally provided voltage on the first of the two self-test channels, bypassing all other input channels and multiplexing circuitry. It verified that a proper conversion and interrupt occured. Should the test fail, the manner in which it fails contributes a great deal to the fault-isolation process which follows. If for example, there is no response at all to the conversion command, it is difficult to fault isolate to a lower level than the total A to D converter subassembly. However, if a conversion and interrupt do occur as a result of the command, but the resulting conversion is out of tolerance, the test program has learned that the conversion process works, but not within specifications, and this additional knowledge aids in fault isolation to a lower level since certain areas of the converter can now be eliminated as the possible cause. The second test step verified conversion capability on the second self-test channel, and that the interrupt timing is correct. The third step indicates that the 28 multiplexed DC inputs are properly switched and accurate, and the fourth step shows that the synchro input channels are properly selected and accurate.

In the process of failing any one of these tests, the test program can provide a great deal of useful fault-isolation information by remembering, not just that the test failed, but in what manner it failed. In addition, useful fault-isolation information is available through analyzing the succession of tests which have passed prior to the failure. If for example, a single analog to digital converter channel fails the fourth test step at only one angle after having passed the first three test steps, it should be possible to isolate the problem to a rather small group of components. Passage of the previous tests has already proven the majority of the A to D converter functions.

To provide the capability of remembering the various failure mode of any test step, certain status and substatus words are reserved in memory for each test step. Each bit in these words is assigned a specific meaning. If during a test, a failure occurs, the test program

sets the appropriate bit in the proper status or substatus word to a one, then continues on to the next subtest. In addition to status and substatus words, other information of significance to the failure is retained in memory and is available for interrogation after the test step has been completed. Examples of such information would be the actual conversion word for an out of tolerance Analog to Digital converter channel or the bit pattern read back to the computer from a register test.

Upon completion of each test step there is a substantial amount of information from that test retained in the computer memory. The specific requirements for automatic testing of this system are verification of operational units and fault isolation of faulty units to the replaceable subassembly level only. To fault isolate to the subassembly level, small part of this retained information is required. In many instances, when a failure occurs there is sufficient information available from the automatic test to isolate the failure to a small group of components. By utilizing the iteration capability of the software and an oscilloscope, the failure can be isolated to a component level.

It should be noted that there are certain test situations in which it is difficult to fault isolate beyond the subassembly level. These situations do not occur often, but when they do, it is usually due to a lack of communication between the computer and the functional area in test. An example of this dilemma would be the failure of the first test step of the Analog to Digital Converter Test, in a mode where no interrupt or conversion occurs. The test program would have learned only one fact, the analog to digital converter is not functioning, and the fault isolation resulting from this failure would be only to the analog to digital converter subassembly itself.

The automatic testing and fault isolation capabilities of this Test Set and Software were considerably greater than required for their specific purpose of LRU verification and fault isolation of the system to the subassembly level. There is a great deal more that can

be done with this type of test equipment and software in the future to provide fault isolation to considerably lower levels, and to require less decision making on the operator's part. Some of the advantages to be realized could be the elimination of lower level test equipment, a decrease in the operation and fault isolation manuals, less training time for equipment operators and a uniform decision process in the fault isolation procedure.

This system automatic test software has been in operational use since early 1973. Throughout this period it has never become necessary to incorporate any changes, corrections or improvements. Time and performance have proven that a logical approach to applying the concepts of software development, pays off.

CONCEPTS OF SOFTWARE DEVELOPMENT

FOR AUTOMATIC

TEST EQUIPMENT TESTING

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SOFTWARE SUITE EVOLUTION

- PROGRAM DEFINITION
- PROGRAM CODING
- AIDS DEVELOPMENT
- SUPPORT DATA

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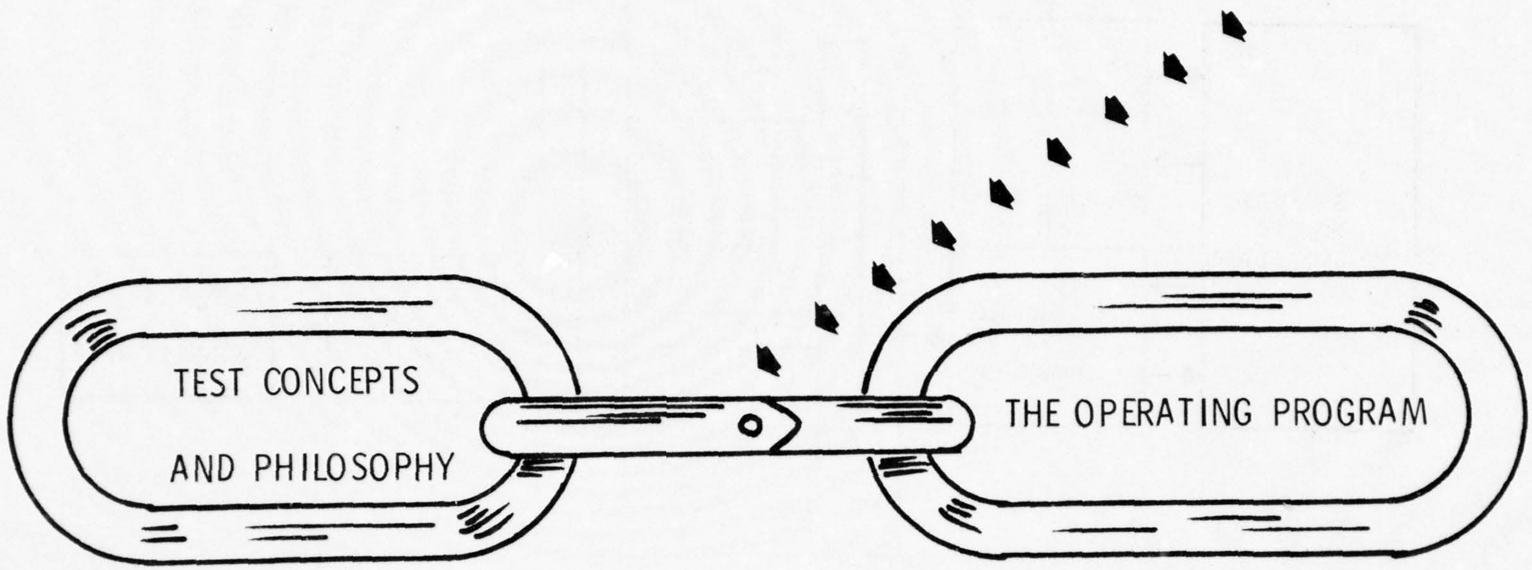
SOFTWARE . . . . THE MASTER LINK



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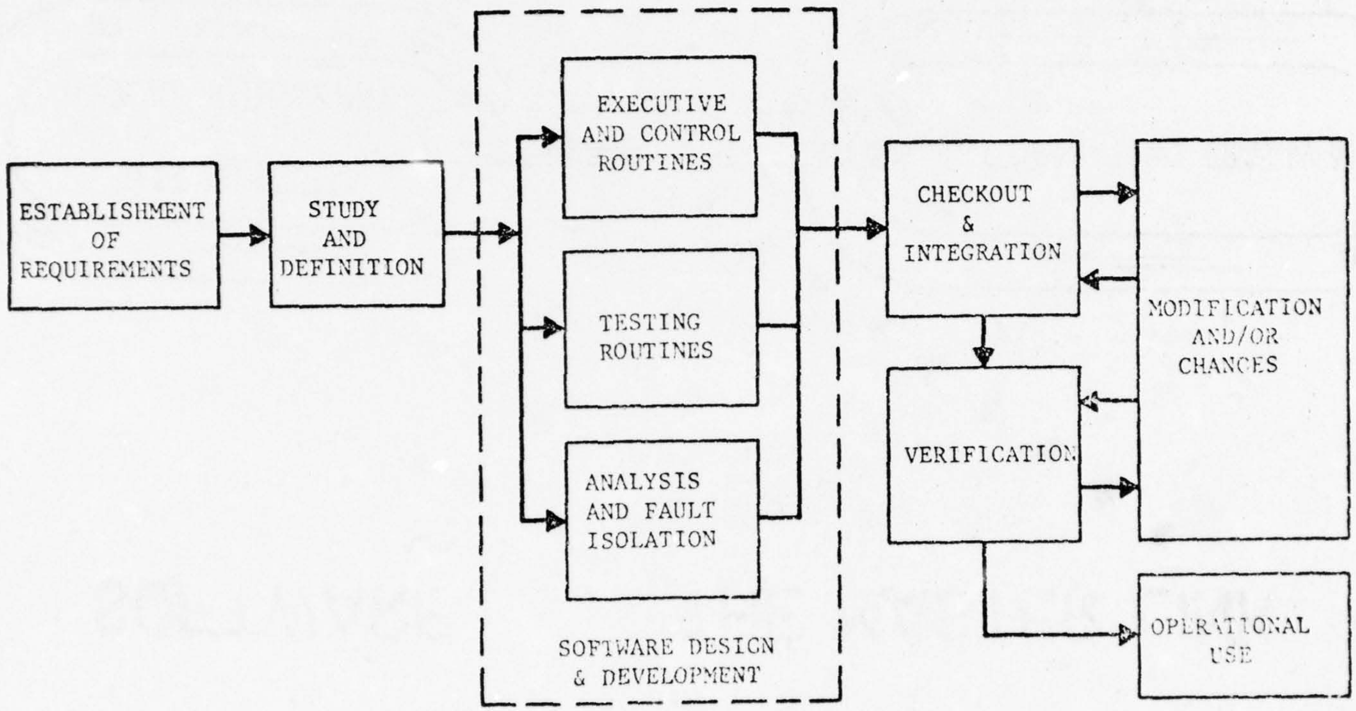
THE AGES OF SOFTWARE DEVELOPMENT



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REQUIREMENTS . . . . .

ANSWERING THE NEEDS

- PROVIDE THE MEANS FOR FAULT ISOLATION TO THE LOWEST LEVEL DESIRED
- AID IN INTERMITTENT FAULT DETECTION THROUGH PROVIDING INDEFINITE REITERATIVE TESTS
- AUTOMATE TEST OPERATIONS TO THE BROADEST DEGREE POSSIBLE
- SIMPLIFY CONTROL AND OPERATION PROCEDURES RELATIVE TO TEST PROGRAMS
- STRUCTURE TESTING TO FIT WITHIN MEMORY SPACE AND REAL TIME CONSTRAINTS

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STUDY AND DEFINITION . . . WHICH WAY TO GO

- SOFTWARE APPROACHES
- METHODS
- OPTIMIZATION
- STRUCTURE AND COMPOSITION
    - SOFTWARE DOMAINS:
        - EXECUTIVE AND CONTROL
        - TESTING
        - ANALYSIS & FAULT ISOLATION

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EXECUTIVE AND CONTROL ROUTINES

THE BASIC FRAMEWORK

- MANAGEMENT/SUPERVISORY DIRECTION
- CONTROL INSTRUCTIONS
- PROGRESS DISPLAY & UPDATE
- TEST SEQUENCING OPTIONS

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TEST ROUTINES

- MODULARITY OF TEST PROGRAMS INCREASES UTILITARIAN ASPECTS
- LIMITING OF FUNCTIONAL AREA TESTED

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ANALYSIS AND FAULT ISOLATION ROUTINES

CONSIDERATIONS:

- TEST TIME VERSUS TEST DOMAIN
- OPERATOR SKILL/TRAINING LEVELS
- SOFTWARE DEVELOPMENT TIME
- BUDGETARY RESTRICTIONS

TYPES:

- MANUAL - INBRED/AIDED
- SEMI-AUTOMATIC
- AUTOMATIC

AUTOMATIC TEST TRADEOFFS

ECONOMY TECHNICAL ADVANTAGES TRAINING LEVEL	VERSUS	MEMORY REQUIREMENTS PROGRAM COMPLEXITY DEVELOPMENT TIME

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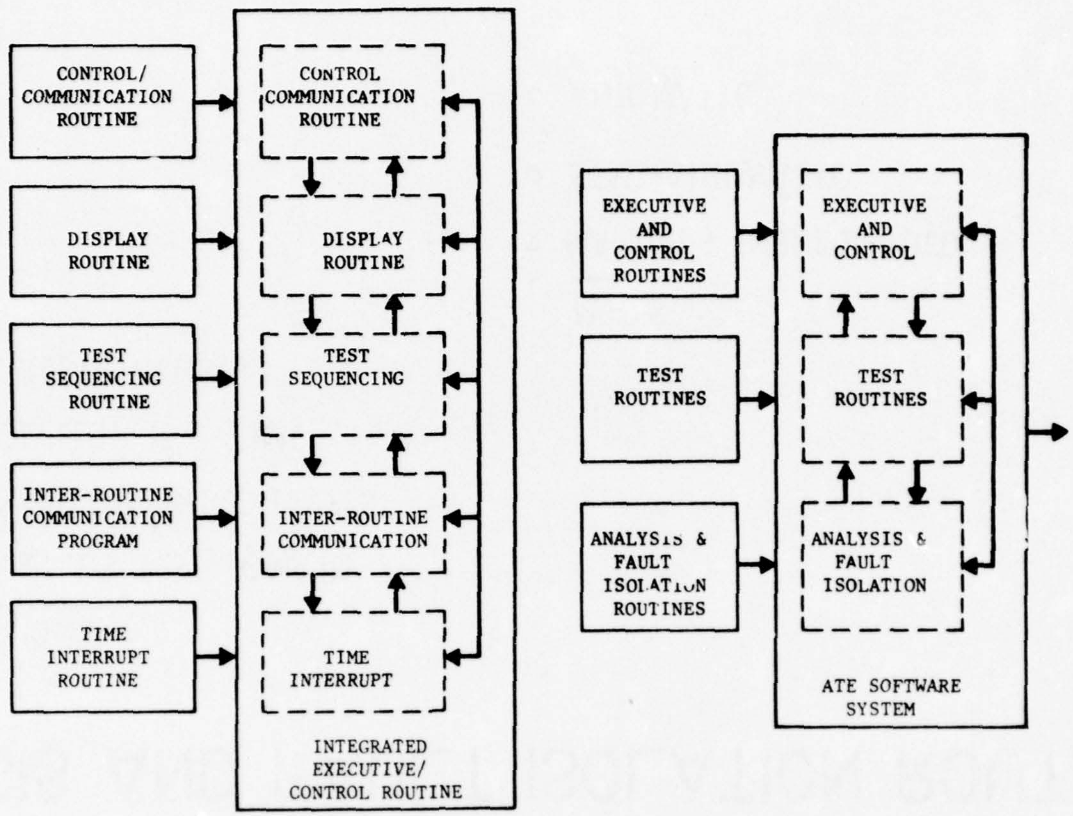
INTEGRATION — GETTING IT ALL TOGETHER



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VERIFICATION — TO BE SURE

- CAPABILITY DEMONSTRATION
- EXERCISE OF FAILURE RESPONSE ABILITY
- RELATED DATA ACCURACY & COMPATIBILITY CHECK
- MODIFICATION/CHANGES IF REQUIRED

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SUMMARY

- REQUIREMENTS ESTABLISHED
- STUDY AND DEFINITION
- SOFTWARE DESIGN AND DEVELOPMENT
- CHECKOUT AND INTEGRATION
- VERIFICATION
- OPERATIONAL USE
- MODIFICATION/CHANGE

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A MODULAR APPROACH TO AUTOMATIC TEST SOFTWARE

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ABSTRACT

An efficient modular software system has been developed, with features that address the problems of automatic test systems. Language statements and the procedures associated with them are formulated in a simplified manner, allowing future ATE languages to be implemented without system level programming.

It is shown how most test languages in existence today can be described in terms of a unified grammar. The ATE system designer first describes the language statements he desires to implement in terms of this grammar. Since the grammar allows statements of most existing ATE languages to be described, it is not necessary to create new languages for new test systems.

However, a test language does not consist of syntax alone. For each statement, the actions that result must be described in terms of procedures, written in a language that allows incorporation into the test system operating software. The resulting actions are specified in terms of the interface of the test instruments and the unit under test (UUT).

The paper describes how the tasks of language developement can be reduced to a cookbook procedure. Statements of any desired test language can be accommodated by these rules of generalized language grammar. Execution can be performed in a compiled or interpretive environment and is independent of the characteristics of the language. This design process yields the added benefit of language standardization, since the procedure is applicable to a broad range of ATE languages.

INTRODUCTION

In recent years, the rapid growth of automatic test equipment has spurred an equally rapid proliferation of automatic test languages. The magnitude of the problem of proliferation of differing test languages can be more fully appreciated by noting that the Air Force currently has an approximate inventory of 108 different types of automatic test systems, and a total of 60 different test languages. This indicates that each of the 60 ATE test language is currently utilized with fewer than two different types of ATE system, on the average.

Since an automatic test system language and its associated operating system represents a large development expenditure, it seems reasonable to undertake development of a single language processor that can serve the needs of a variety of differing automatic test systems.

LEVELS OF LANGUAGE

As an automatic test software system passes through the stages of definition, design, programming, integration, and checkout, and is finally placed on-line, several types of programming skills are incorporated into the total software product. In a recently completed ATE system, the following programming activities were in evidence:

1. LANGUAGE PROCESSOR: Assembly language programming to create the language processor and operating system. In the case considered, an interpreter was developed for use as the test language processor. The operating system was selected from those available from the computer vendor. The interpreter remains resident during the excution of a test program. The source coding of the application program is loaded into the interpreter at the time that program execution is desired. The source program resides in the core memory of the computer throughout program execution. The interpreter executes the program directly from the source language by inspecting each language statement at the time it is to be executed, then performing the necessary operations. The interpreter maintains symbol tables, variables, and intermediate storage as required for application program execution, and executes statements according to the numerical order of their line numbers.

The use of an interpreter as a test language processor offers the advantages of speed of application program development, since the task of compilation is eliminated. Furthermore, an interpreter allows application programs to be integrated with their respective end items in an interactive manner, allowing application program bugs and changes to be serviced through manual exercise of the test language, at the test station.

2. DRIVERS: Assembly language programming to provide drivers for the electronic instruments, stimuli, and switching devices provided the ATE set. The device drivers include all coding of input/output instructions necessary to transfer data to the hardware devices. Since the driver routines are ultimately incorporated into the operating system, they generally perform little or no data manipulation. Their main purpose is to perform the input/output protocol with the hardware devices, to transfer single units of data.

3. SERVICE ROUTINES: Coded in either Fortran or Assembly language. These routines perform the algebraic calculations and logical decisions necessary to execute individual language statements. At run-time, these routines receive the parameters from the language state-

ments, determine the actions that need to be taken, and call the drivers necessary for physical input and output. Since certain language statements may require several I/O actions to various devices, the service routines are responsible for calling the instrument drivers in the necessary order. It is also possible for a statement of the language to have no requirement for I/O, as in the case of a data conversion statement. In these cases, the service routine performs the computation but does not perform I/O actions.

4. LANGUAGE DEFINITION TABLES: Assembly language coding to specify the format of the source language. As will be described later, the source language is divided into two parts. The invariant part of the language does not reflect the instrument complement of a particular ATE console, but contains language statements that relate to computation-based actions that would normally be found in an algebraic language such as Basic or Fortran. This part of the test language is defined within the interpreter itself. The augmented language statements pertain to the instruments and special hardware devices that are present on a particular ATE console. Different instruments and devices present on different types of ATE require their own sets of statements of the augmented language. The augmented language is defined in a tree-organized table that becomes a part of the total software package. The statements that augment the invariant language to provide a capability of exercising specialized instruments, stimuli, and switching devices are defined in this table.

5. APPLICATION PROGRAMS: Programs that are written in the application programming language of the ATE. These programs utilize the language to perform tests upon the end item assemblies. Several such application programs may be resident within the disc storage unit of the ATE system; however, only one program can be executed at a time.

6. OPERATOR COMMANDS: The test station operator enters commands into the terminal unit at the ATE console to select an application program for execution and initiate it. In a sense, the operator commands can be considered as the equivalent of an extremely high level, concise language. Since the level of a language can be measured by the amount of action that results from a single statement, it can be seen that the single operator command that invokes execution of an entire program file has an extremely high language level. In fact, the ultimate purpose of all lower levels of programming is to provide the ATE system operator with a complete software system that allows him to execute entire end item test programs with a single command. This ultimate statement of the operator command language has the following form:

RUN <file>

where <file> designates the program file to be called from the disc storage unit and executed. Other operator commands allow program files to be loaded, stored, listed or edited.

Each of the foregoing levels of programming serves to provide the foundation for higher programming levels. Furthermore, programming at each of these levels is performed at different points during the progress of the ATE software effort, and by different skill levels. The chart in Figure 1 shows the skill levels necessary for each phase of the software effort.

RECURRING DESIGN

In an ATE program in which a number of identical ATE systems are built to the same drawings and specifications, the recurring effort to provide each ATE with an identical set of software is not extensive or complex. In most cases, the software effort to support a recurring hardware build consists of duplicating the discs or tapes to be shipped with the system. Certification may be performed to verify that they are true copies of the original discs or tapes. However, a greater software effort is required when a new item of ATE is first designed. Assuming that a level of maturity has been reached in the software language processor, it should not be necessary to design a new language in totality for each new or modified ATE design. However, it can also be seen that a newly designed or modified ATE system will inherently have specialized stimuli, measurement, and switching devices that may not have been present on previous systems. For this reason, certain defined tasks must be performed to develop the software for a new ATE system. These tasks relate to the design of suitable language statements to accomodate the intrumentation devices, and the programming of the drivers, service routines, and language definition tables to be appended to the previously existing software processor. Since these tasks must be performed for each new item of ATE, they are designated as recurring design. The tasks involved in the recurring design phases are well-defined, and can be performed according to a cookbook-like design procedure. The new language statements that result from this process will be perfectly integrated with the statements inherent in the unmodified part of the language processor.

After a new set of statements is appended to the language processor, application programs must be written, using the new statements that have been implemented. The tasks of application program generation are performed for each end item to be tested.

The design and programming tasks that must be performed for new ATE systems are summarized in the chart of Figure 2.

INVARIANT LANGUAGE SET-BASIC

The language system considered here includes a fundamental, invariant language that implements the language functions pertaining to arithmetic operations, operator inputs and outputs, printout control, program execution jumps and loops, and data file manipulation. An extended set of Basic Language is utilized as the invariant language. As such, the language is used as the framework for controlling the execution of application tests, performing data reduction of test results, producing printouts, and performing any other associated data processing or computation tasks. The language includes the following types of statements:

ABORT	Issues hardware master clear to reset all instrumentation and perpipheral devices.
BOOLEAN AND	Boolean "and".
BOOLEAN OR	Boolean "or".
BOOLEAN XOR	Boolean "exclusive or".
CHAIN	Automatic linking to another program.
CLOSE	Closes a file.
COM	Specifies common array or variable.
DATA	Specified data.
DIM	Specifies array size.
DO XF	Enable XF Flag.
END	Terminates execution. (not required as last statement in program)
FOR	Begins loop.
GO TO	Transfers control.
GO TO...OF	Multibranch transfer.
GOSUB	Executes subroutine.
GOSUB...OF	Multibranch subroutine.
IF	Logical test.
INPUT	Data entry from terminal.
LET	Assignment operator.
MAT	Matrix operations
NEXT	End of loop.
OPEN	Opens a file.
PRINT	Display on terminal, or output to file or device.
READ	Read value from data blocks or file.
REM	Remark.
RESTORE	Reset data pointer.
RETURN	Subroutine return.
RUN	Call program.
SKIP XF	Disable XF Flag.
STOP	Terminates execution.
WAIT	Time delay.
(implied LET)	Assignment operator.

Algebraic operators and intrinsic functions also form a part of the extended Basic Language. The usage and syntax of the language follow all conventions of the standard Dartmouth Basic Language.

AUGMENTED LANGUAGE SET

The syntax of Basic Language can be expanded by the addition of language statements, to give specialized capabilities to particular system configurations. After language statements are added to the software package, they become integral elements of the user language The set of statements that are added to the standard Basic syntax are collectively referred to as the Augmented Basic Language. Once installed in a particular software system configuration, a set of Augmented Basic Language statements becomes a permanent addition to that single system. It then provides a customized user language facility, which can be used in programming the specialized tasks to be performed at the test station.

The use of Augmented Basic Language statements offer several advantages and unique features to the programmer of application programs. Since the formats of the allowable statements are formulated by those having a thorough knowledge of the system functional details, all input/output requests to specialized devices are made through the Augmented Language statements, so that all I/O calls are made with proper formats and parameters. Furthermore, formatting and manipulation of input/output data is performed by the service routines for the Augmented Language statements, thus relieving the application programmer of these repetitive tasks.

The structure of the Augmented Language demands that the application programmer enter all required parameters in each statement. Both omissions and inclusion of extra parameters generate error messages, which cite the offending statement. Since the syntax requirements of the Augmented Language statements must be properly fulfilled at the time the statement is entered, it is inherently immposible for the interpreter to accept source language statements having improperly constructed I/O calls. In this manner, improper I/O calls are rejected by the interpreter as being syntactically incorrect.

2. STRUCTURE OF AUGMENTED STATEMENTS: The Augmented Langauge statements are composed of the following elements, which are utilized as described below to construct complete statements:

ELEMENT	DESCRIPTION
verb	The initial word of a statement, immediately following the statement number and optional flag. A verb consists of an ASCII character string.
noun	A noun consists of an ASCII character string. Both verbs and nouns may consist of any of the 64 printable ASCII characters except (or [.
(and)	The left and right parenthesis characters are

utilized to delineate lists of parameters within a statement. All parameters such as variables, arithmetic constants, arithmetic expressions, and strings enclosed within quotes, are contained between left and right parenthesis.

parenlist — A list of parameters, seperated by commas, and enclosed within parenthesis. These parameters contain quantities that may be determined at the time the application program is written (constants) or may be determined at run-time (variables or expressions). The parameters in the parenlist may be any of the types described below.

C-parameter — A mathematical constant, within the approximate range of $\pm 10^{38}$. Integer or fractional values may be given, since the numercial values are stored internally in floating point representation in either case. Values may be given in free-form format, with decimal point or exponential representation utilized as desired.

V-parameter — A single variable. The given variable may be either simple (not subscripted) or subcripted. If the variable is subscripted, then the subscript may be any valid Basic language subscript expression.

S-parameter — An ASCII string, enclosed within double quotes. The string may include any of the 64 printable ASCII characters except for the double quote. The string may be of any length, so long as the total statement length does not exceed 72 characters. Note that S-parameter strings differ from the strings of verbs and nouns in that verbs and nouns are determined at the time a set of language statements is designed, while S-parameter strings are determined at the time a particular application program is written. Verbs and nouns are therefore considered as elements of the language. S-parameters are strings utilized by application programmers for particular uses within a program.

G-parameter — This parameter may be either a constant, variable, string, or expression. If the G-parameter consists of a constant, variable, or string, then the descriptions of the C-parameter, V-parameter, or S-parameter, respectively, will apply. Otherwise, the G-parameter may be any valid Basic language expression. Such expressions may consist of variables or constants, in combination with arithmetic operators, logical operators, or functions, configured according to the general syntactical rules for Basic expressions.

Complete augmented Basic language statements are described by the following Backus-Naur representations:

```
<augmented statement> ::=<verb>|
                          <augmented statement>
                                <noun>|
                          <augmented statement>
                                (<parenlist>)

<verb> ::= < predetermined ASCII string,
             chosen for relevance to ATE
             function>

<noun> ::= < predetermined ASCII string,
             chosen for relevance to ATE
             function>

<parenlist> ::= <G-parameter>|
                <C-parameter>|
                <V-parameter>|
                <S-parameter>|
                <parenlist>, <G-parameter>|
                <parenlist>, <C-parameter>|
                <parenlist>, <V-parameter>|
                <parenlist>, <S-parameter>

<G-parameter>::= <expression>|<C-parameter>|
                 <V-parameter>|<S-parameter>

<C-parameter>::=<constant>
<V-parameter>::=<variable>
<S-parameter>::="<string>"
```

In the above descriptions, symbols have the following meanings;

::= "is defined as"

| "or"

<> enclose an element of the language

All other symbols that appear indicate actual characters or punctuation marks in the various statements.

The above syntax requirements delineate the structure of single statements of the Augmented language.

AUGMENTATION PROCEDURE

In order to design a set of Augmented language statements, it is necessary to first delineate the specific functions of the devices to be controlled. In cases where the Augmented language statements are utilized to perform computational processes rather than input-output actions, the parameters and formats to be passed to the process must be defined.

After definition of the individual functions to be exercised, a set of language statements must be constructed. The individual statements must conform to the syntax requirements described above. Finally, the statements must be arranged in a sequential order and described in a terminology that allows easy coding for incorporation into the interpreter.

STEP 1: Describe all desired statements to be added to the language in a form consistent with the syntax requirements given above in Backus-Naur form. At this time, all verbs and nouns must be selected. Further, the desired order of each of the selected elements within a statement must be determined. Each parenthesis list to be included within the statement must be selected, along with the allowable forms of its constituent terms. The parenthesis lists to be utilized within a given statement must have a definite number of terms of selected types, with the following exception: as an option that may be invoked in the design of a statement, a parenthesis list may be allowed to have an indefinite number of terms, so long as the optional terms are all of the same type, and are all located to the right of the terms whose presence is mandatory. Phrased differently, an option is available whereby the rightmost group of terms within a parenthesis list may be of an indeterminate length, but must be of the same type.

STEP 2: Arrange the desired statements of the Augmented language into a linguistic tree. The tree then defines legal word sequences for the set of statements. It represents, in graphic format, how the verbs, nouns, and parameters of the statements are arranged. All legal statements will lie along the branch structure of the tree. Conversely, statements that do not conform to the linking of tree branches are not legal, and will be rejected by the language interpreter. Figure 3 shows a typical linguistic tree.

STEP 3: Encode the syntax tree generated in the previous step into machine readable coding. The encoded linguistic tree will ultimately become incorporated into the interpreter, and will be utilized for syntax checking of source language statements.

STEP 4: Perform programming necessary to generate service routine and driver modules to perform interpretive execution of each statement of the Augmented Basic Language. The programming may be performed in any convenient language, such as Fortran, Algol, or Assembly language.

STEP 5: Combine the elements of the augmented statements (encoded syntax tree, service routines, and drivers) into a single software package. The task of creating a single software package containing the standard Basic module is performed through use of the Loader, or Linkage Editor. The result is a software package that has been customized to the requirements of a specific item of ATE, with its own particular complement of instruments and stimuli devices. The structure of the customized interpreter and the relationship between the various elements is shown in Figure 4.

CONCLUSIONS

The creation of a new programming language and operating environment for each new automatic test system has been widely proven to be highly inefficient from the standpoint of the amount of effort, funding, and risk that are entailed. The modular approach described here offers the following improvements:

- Eliminates the need to define and specify the total language and operating environment for each item of ATE.
- The only part of the test language that must be defined is the set of statements that interface with the test station hardware and instrumentation.
- Assures that the language statements used for calculations and program control are identical across ATE systems of different types.
- Assures that the operator commands and operating procedures are identical across a range of differing ATE systems.
- Provides the full data processing capability of Basic language in the same software package utilized for automatic test operations.
- Gives engineering personnel an additional measure of familiarity with the language, since most engineers already know Basic language.
- Allows ease of documentation and configuration control due to the modularity of the software system.
- Atlas-like statements can be implemented to allow program portability from other ATE systems, and to allow easy application program coding from test specifications written in Atlas.
- Use of the same language format and operating environment allows several types of ATE to follow the same programming conventions.
- The same language syntax can be processed by an interpreter or a compiler.

PROGRAMMING ACTIVITY	PERFORMED BY
1. LANGUAGE PROCESSOR	SYSTEM PROGRAMMER
2. DRIVERS	HARDWARE ORIENTED PROGRAMMER
3. SERVICE ROUTINES	SENIOR PROGRAMMER
4. LANGUAGE TABLES	SENIOR PROGRAMMER
5. APPLICATION PROGRAMS	APPLICATION PROGRAMMER
6. OPERATOR COMMAND ENTRY	CONSOLE OPERATOR (USER)

FIGURE 1.

PROGRAMMING ACTIVITY	RECURS FOR
1. LANGUAGE PROCESSOR	ONCE ONLY
2. DRIVERS	EACH ATE SYSTEM DESIGN
3. SERVICE ROUTINES	EACH ATE SYSTEM DESIGN
4. LANGUAGE TABLES	EACH ATE SYSTEM DESIGN
5. APPLICATION PROGRAMS	EACH END ITEM TESTED
6. OPERATOR COMMAND ENTRY	EACH PROGRAM EXECUTION

FIGURE 2.

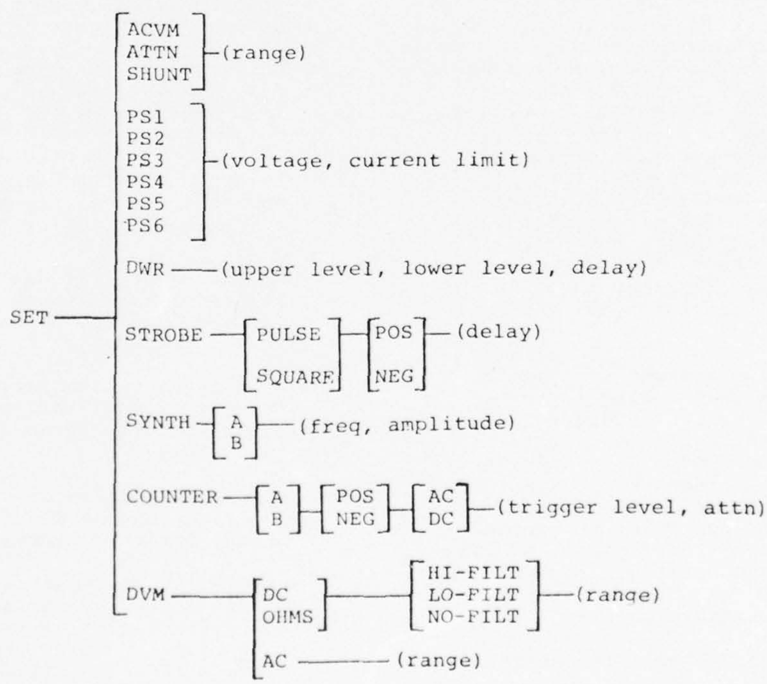

FIGURE 3A

```
          ┌ DVM ─────────(result)
          │
MEASURE ──┤ DISTORT ─────(freq, ans in db)
          │              ┌ FREQ   ┐
          │              │ PERIOD ├────────(timing, result)
          │ COUNTER ─────┤ INTVL  ┘
          │              │ START
          └              └ STOP ───────────(result)
```

FIGURE 3B

<u>CUSTOMIZED STATEMENT EXAMPLES</u>

```
10  SET POWER PHASE A ON
20  SET SYNCHRO HEADING (90) DEGREES
30  MEASURE STATUS (S)
40  IF S=0 THEN 1234
50  MEASURE RESOLVER AZIMUTH (A3)
60  SEND SERIAL WORD (2) DATA (64)
70  RECEIVE SERIAL WORD (5) DATA (D5)
80  SET POWER OFF
90  SET COUNTER A POS AC (2.2, 1)
```

FIGURE 3C

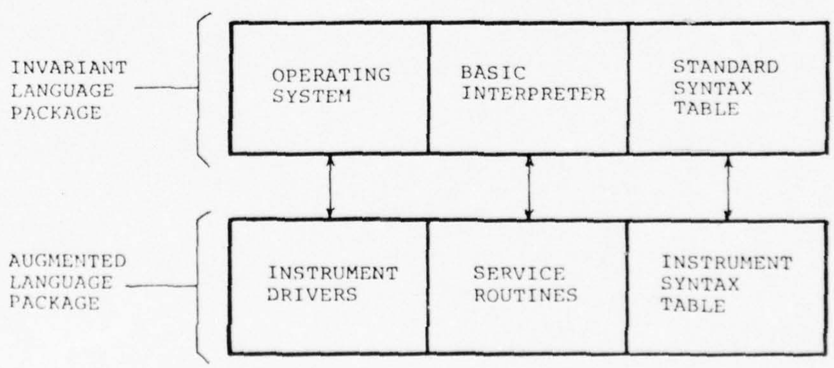

FIGURE 4

Standardization of

Automatic Test Equipment Software

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BENEFITS

1. IMPROVE COMMUNICATION
2. SIMPLIFY TRAINING
3. ESTABLISH BASELINE
4. REDUCE DEVELOPMENT COSTS
5. REDUCE MAINTENANCE COSTS
    - INCREASE PRODUCTIVITY
    - PROVIDE COMMON TEST TOOLS
    - IMPROVE RELIABILITY
    - IMPROVE MAINTAINABILITY

CRITERIA

- READABLE
- WRITEABLE
- TRAINABLE
- FLEXIBLE
- EXPANDABLE
- REHOSTABLE
- RETARGETABLE

STUDIES

- DOD HIGHER ORDER LANGUAGE STANDARDIZATION

- DEFENSE AUTOMATIC TEST EQUIPMENT LANGUAGE STANDARDIZATION

APPROACHES

1. DOD STANDARD
2. OPERATIONAL PERFORMANCE ANALYSIS LANGUAGE/DATELS
3. ATLAS WITH EXTENSIONS

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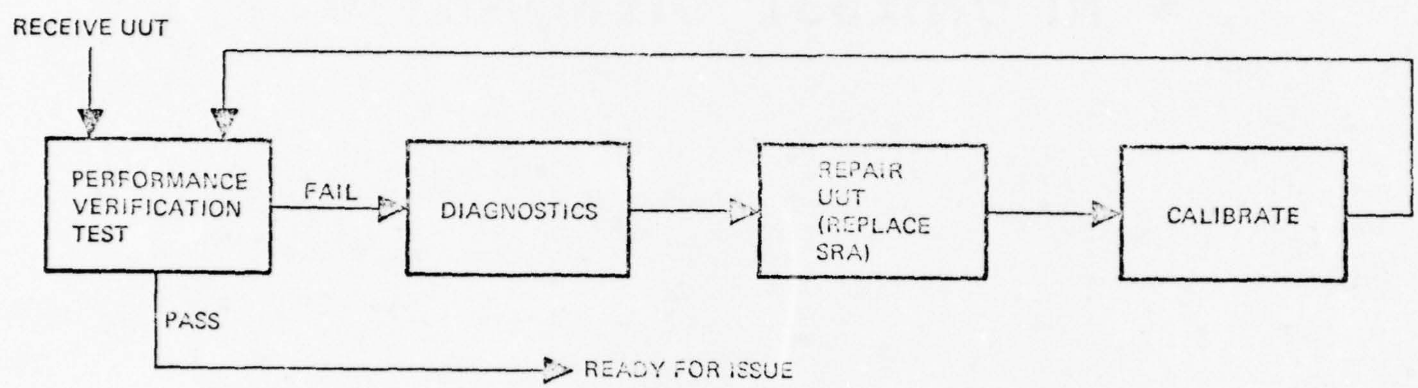
DIAGNOSTIC TESTING IN A REAL TIME ENVIRONMENT

Litton GUIDANCE AND CONTROL SYSTEMS

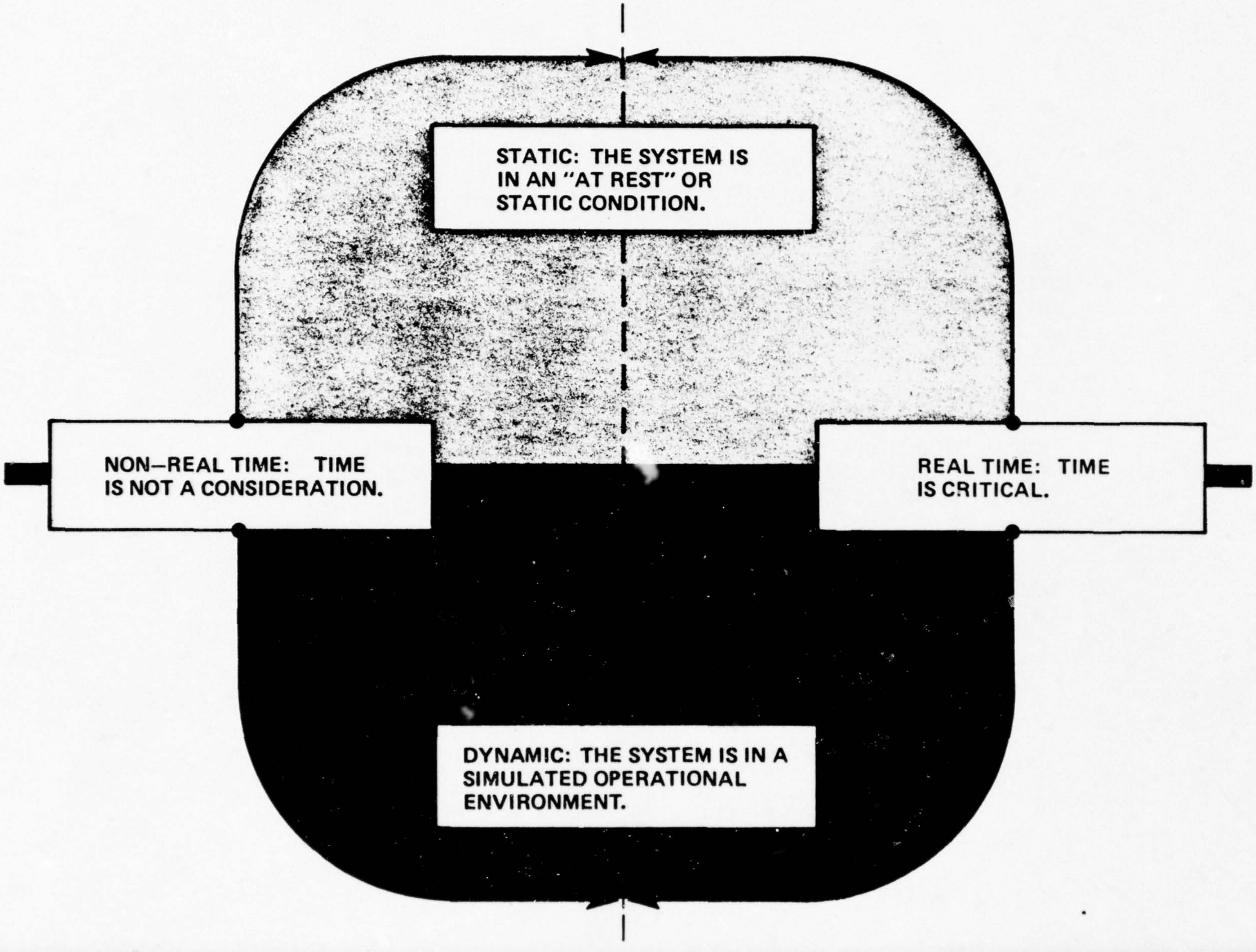
F. Blaize Cooke
Manager T.E. Software

TESTING PURPOSE

- VERIFY THE INTEGRITY OF A UUT AND PRONOUNCE THE UUT READY FOR ISSUE (RFI)
- DETERMINE IF THE UUT IS FAULTY AND IDENTIFY THE FAULT IN ORDER THAT THE UUT MAY BE REPAIRED IN A TIMELY FASHION



TESTING TECHNIQUES



TESTING OPERATION

REAL TIME TESTING IS CONDUCTED AT LITTON UTILIZING THE MULTIPLEX FOREGROUND AND BACKGROUND MODE OF OPERATION ON THE COMPUTER.

I. FOREGROUND MODE.

THE TEST SYSTEM COMPUTER PERFORMS THE SAME FUNCTION AS THE FLIGHT COMPUTER TO SEQUENCE THE UUT THROUGH THE OPERATIONAL MODES AND PERFORM ALL LOOP CLOSURES. ALL FLIGHT CONDITIONS REQUIRED ARE SATISFIED IN REAL TIME.

II. BACKGROUND MODE.

THE PERFORMANCE VERIFICATION TEST PROGRAM IS EXECUTED TO VERIFY THE INTEGRITY OF THE UUT. WHEN ANY FAIL CONDITIONS ARE DETECTED THE PROGRAM AUTOMATICALLY BRANCHES TO DIAGNOSTICS WHERE THE FAULTY SHOP REPLACEABLE ASSEMBLY (SRA) IS ISOLATED AND IDENTIFIED.

SPECIAL MONITORING: THE TEST SYSTEM ALSO CONTINUOUSLY MONITORS THE UUT TEMPERATURE AND POWER FOR ABNORMAL CONDITIONS.

REAL TIME TESTING REQUIREMENTS

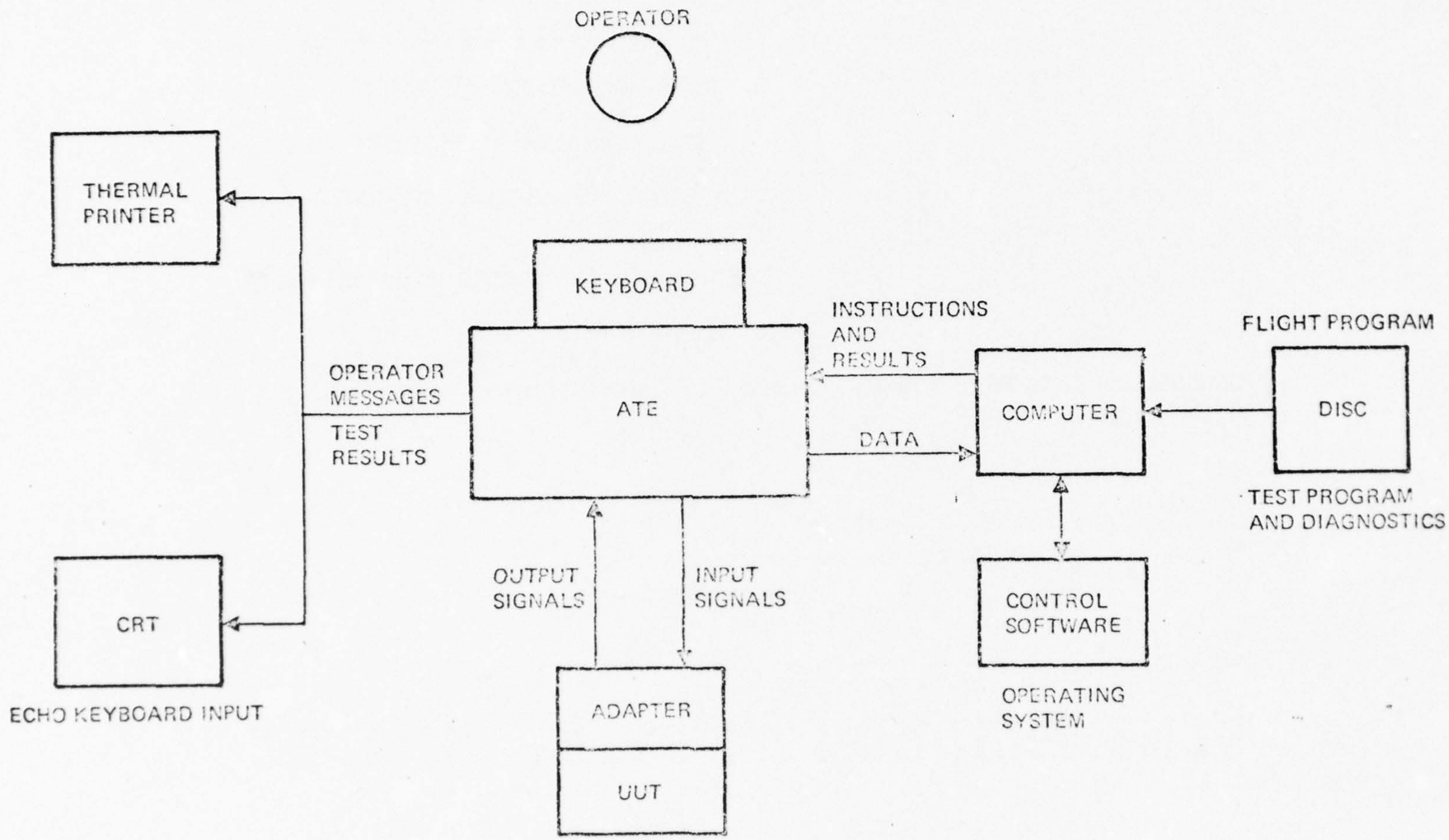
- HARDWARE MUST HAVE CAPABILITY TO PROVIDE ALL REAL TIME INPUTS AND TIMING REQUIRED BY THE UUT

- SOFTWARE MUST INCLUDE THE FOLLOWING:

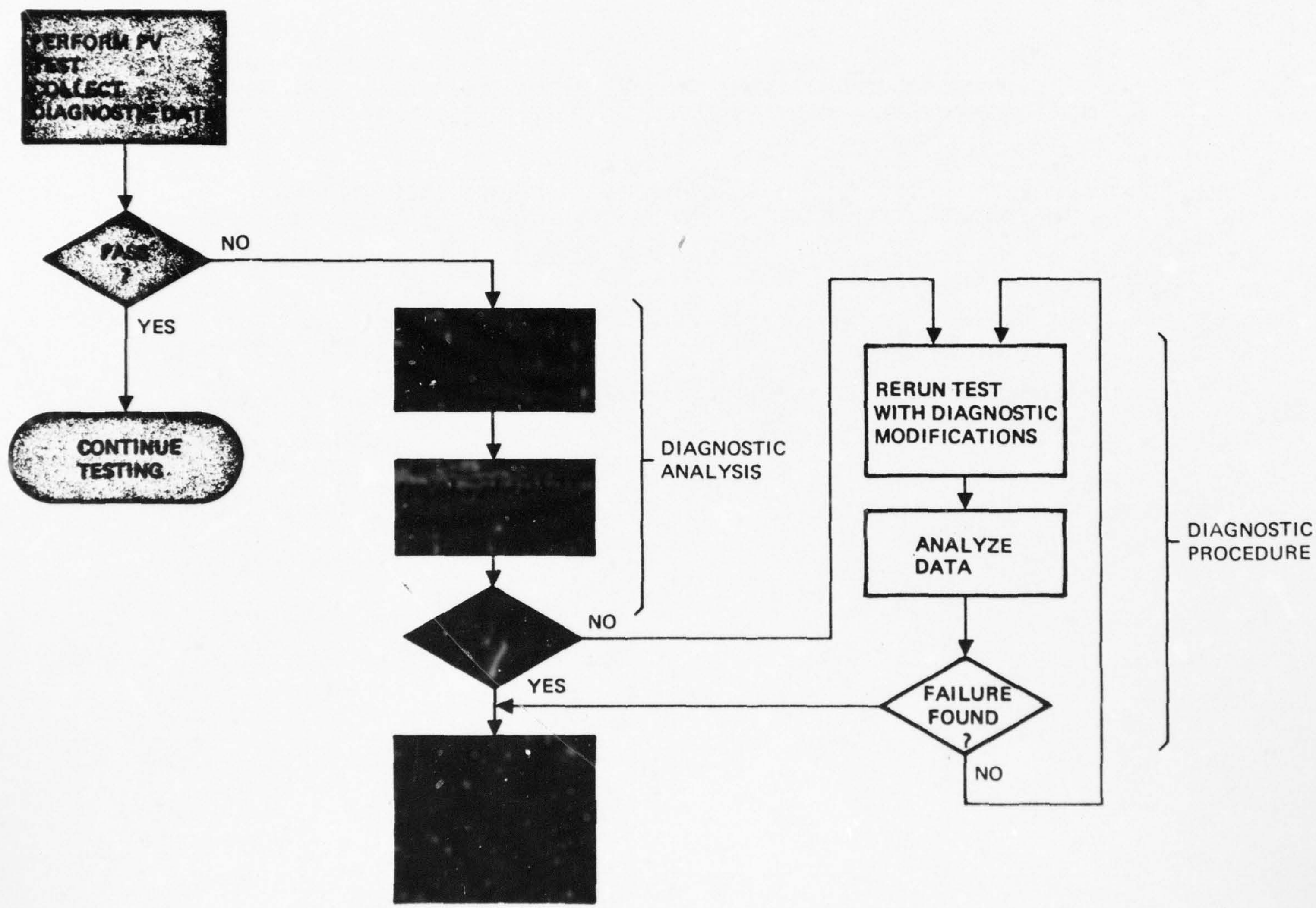
  - REAL TIME OPERATING SYSTEM
  - MULTIPLE PARTITIONS
  - REENTRANT SUBROUTINES
  - INTERRUPT/TIMING SYSTEM
  - MULTITASKING CAPABILITY

AUTOMATIC TEST SYSTEM

THE TEST SYSTEM IS A COMPUTERIZED TEST STATION WHICH CONTAINS THE CAPABILITY TO EXECUTE A PERFORMANCE VERIFICATION TEST AGAINST A UUT TO VERIFY THAT THE UUT IS RFI



GENERALIZED DIAGNOSTICS



- DIAGNOSTIC ANALYSIS
    - BASED UPON EVALUATION OF DATA COLLECTED DURING GO–PATH TESTING
    - WHEN "FAILURE" OCCURS:
        - IDENTIFY FAULTY SRA
        - DIRECT FURTHER FAULT ISOLATION TESTING CALLED "DIAGNOSTIC PROCEDURE" IF SRA NOT IDENTIFIED
    - THIS METHOD CONSISTS OF COLLECTING DATA DURING PV EXECUTION, THEN AFTER DETECTING A FAILURE TO EXAMINE THE DATA AND ATTEMPT TO DETERMINE THE PROBLEM

- DIAGNOSTIC PROCEDURE
  - COMPUTER DIRECTED TESTING AVAILABLE TO ISOLATE FAILED SRA VIA:
    - PERFORMANCE OF SPECIAL TESTS
    - PROBING
    - SRA SUBSTITUTION
  - THIS METHOD CONSISTS OF EXECUTING TESTS SIMILAR TO THOSE IN THE PV, BUT CHANGING THEM SO AS TO EMPHASIZE A PARTICULAR FAULT. IT MAY ALSO INCLUDE CHANGING THE TEST HARDWARE STRUCTURE SUCH AS OPENING CONNECTORS, USE OF BREAKOUT CABLES, COMPUTER DIRECTED CARD REPLACEMENT AND PROBING.

EXISTING FACTORY
ACCEPTANCE TEST PROCEDURE (ATP)

TEST #1

1. INPUTS
2. DATA COLLECTION
3. DATA REDUCTION
4. PASS/FAIL

TEST #2

TEST #3

DIAGNOSTIC
ANALYSIS

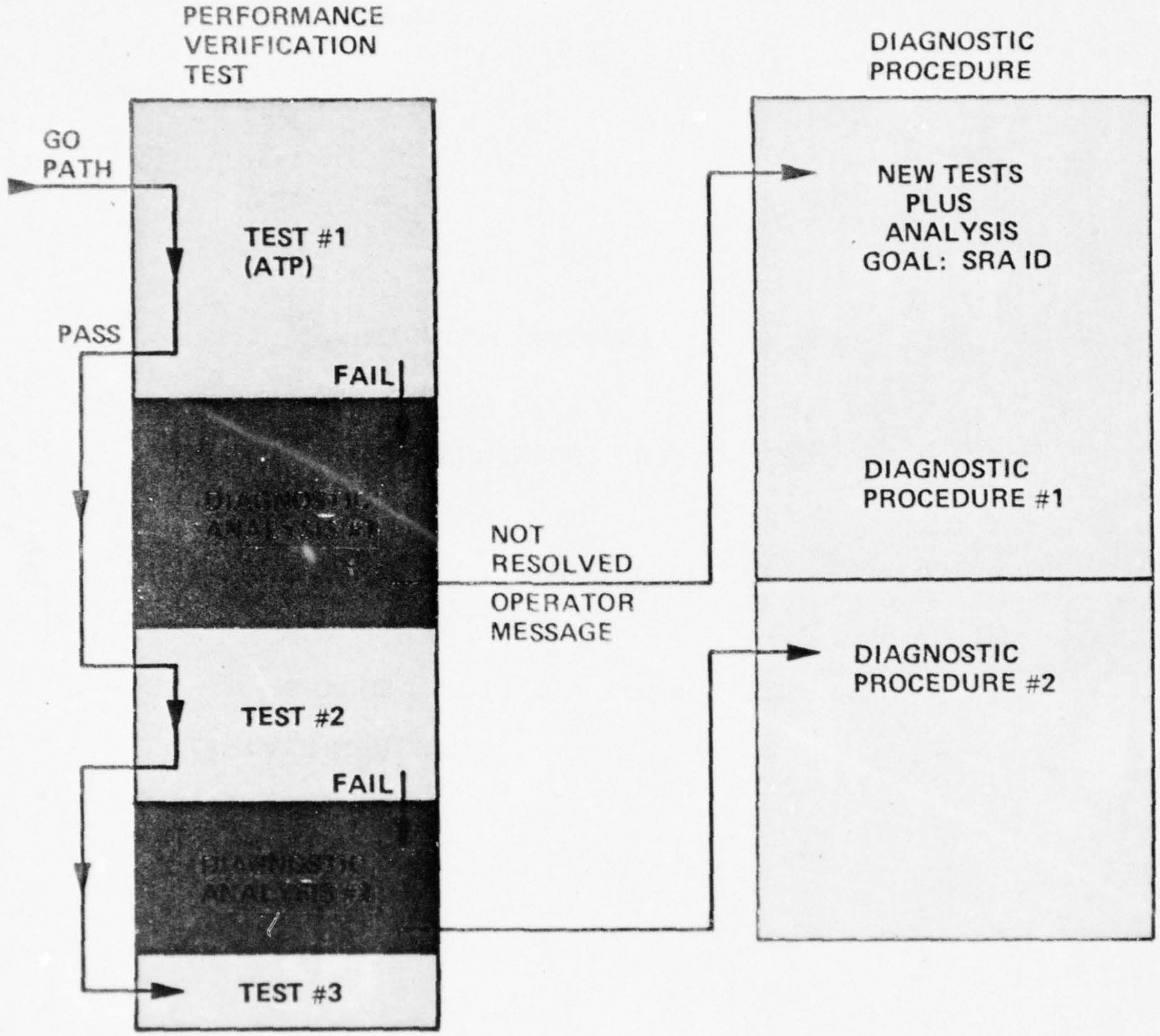
DA #1

1. ADDITIONAL DATA COLLECTION
2. DATA REDUCTION
3. ANALYSIS
4. SRA ID

DA #2

DA #3

TEST/UUT HARDWARE
STRUCTURE NOT
CHANGED.



TESTS ARE PERFORMANCE ORIENTED. IS THE UUT RFI?

TESTS ARE DIAGNOSTIC ORIENTED. WHAT IS WRONG WITH UUT?

LITTON COMPUTERIZED TESTING APPLICATIONS

- REAL TIME TESTING
  - CAINS INERTIAL MEASUREMENT UNIT (IMU)
  - SRAM IMU
  - F–15 INERTIAL NAVIGATION MEASUREMENT UNIT (INMU)
- REAL TIME TESTING INCLUDING DIAGNOSTICS
  - CAINS IMU
  - CAINS GIMBAL ASSEMBLY

ATTENDEES

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FOREWORD

The Joint Services Data Exchange Group for Inertial Systems is an informal organization through which maintenance experiences are exchanged in an attempt to improve the reliability and maintainability of inertial equipment. It is a medium for the exchange of information and ideas among the various support agencies, users, maintenance facilities, manufacturers and designers. It provides a rapid feedback of design deficiency information to effect improved and more efficient maintenance support.

BACKGROUND

The Joint Services Data Exchange Group for Inertial Systems was formally established in March 1969. Its basic objectives, principles and concepts began about one year earlier through a series of conferences hosted by the Air Force Aerospace Guidance and Metrology Center. The organization has progressively grown in interest and attendance. Its participants now encompass about every segment of the international inertial equipment community.

APPROACH

The key to any successful conference or gathering of individuals to swap ideas and solve each others problems is the climate or environment established for such an exchange. It was recognized that an acceptance by the participants to freely discuss mutual problems would meet with certain resistance. Equally, it was recognized that a special vocabulary exists in our profession and some degree of translation and understanding must evolve before a meaningful exchange could be expected. The group architects realized the real benefits and ultimate payoff would come from an exchange that would involve all defense agencies, designers, manufacturers, repair shop, as well as commercial aircraft operators. A plan was designed to slowly expand participation and overcome reticence to communicate problems. The first meeting included Air Force personnel. The circle of interest was then enlarged to include all defense agencies. Later the equipment manufacturers and commercial aircraft operators were added. As the last phase in rounding out the program selected international organizations have been invited to participate. Each conference has experienced a progressive buildup in attendance, enthusiasm and interest.

ORGANIZATION AND OPERATION

Participation in the conferences includes representatives from the Air Force, Army and Navy Materiel Commands and agencies having a responsibility for, or an interest in, specifying, developing, logistics planning and support, or using inertial systems and/or components. This group will also include representatives from other government agencies, user agencies, consultant organizations, manufacturers, commercial airlines, selected international organizations and selected non-US carriers and manufacturers.

The hosting of the conferences is rotated among the participating organizations. Where possible an attempt is made to hold the conference at a facility connected with the inertial systems community. If the host is engaged in the repair/test of inertial systems a tour of these areas is included on the agenda.

The Aerospace Guidance and Metrology Center (AGMC) functions as Secretariat and provides a permanent secretary for the group. A planning group with representation from the major participating elements of the group (e.g., government agencies, consultant organizations, airlines, etc) is established to coordinate and guide the various group activities. In advance of each conference a visit is scheduled to the designated host organization to finalize all administrative details for the next group conference. Under normal circumstances the host for a conference is expected to provide facilities (e.g., auditorium, hall, etc) that will accommodate the number of participants, audio visual equipment and operation, clerical and other administrative support as may be required. The host will identify a focal point to handle reservations for accommodations, protocol arrangements, transportation, etc.